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UNDERWATER EXPLOSION TEST CASES

Andrew B. Wardlaw, Jr.

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13. ABSTRACT (*Maximum 200 words*)

Simulation of underwater explosions is an essential component of platform survivability and weapon lethality assessments. Success at this task requires predicting target loading, which primarily occurs as a consequence of the initial shock and subsequent bubble collapse. These damage mechanisms occur on time scales that differ widely, typically on the order of microseconds for the shock and milliseconds for collapse. Successful prediction of these events requires numerical techniques that can capture strong shocks and the interface between fluids with density ratios of 1000:1. This report describes a set of 19 test cases that exhibit such phenomena. These problems are divided into three groups: one-dimensional with fixed boundaries, two- and three-dimensional with fixed boundaries, and one-, two, and three-dimensional problems with moving boundaries. The specification of these problems includes grid size for a fixed Cartesian mesh.

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FOREWORD

This report documents a series of test cases developed to evaluate the suitability of numerical methods to simulate underwater explosions. The focus in these cases is to test the capability of numerical schemes to capture strong shocks and material interfaces, particularly when those interfaces involve large density jumps. This work was supported by the Office of Naval Research.

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1. INTRODUCTION

The Naval Surface Warfare Center, Indian Head Division has an abiding interest in developing and applying numerical techniques to simulate underwater explosions. Important ingredients in such simulations are the accurate modeling of strong shocks, the capturing of complex interfaces between fluids with density ratios as large as 1000:1, and the ability to successfully predict the interaction between the fluid and an imbedded, non-rigid body. To facilitate the development of improved numerical methods, a set of test cases has been assembled that contains these flow field features. These cases have been tailored to a specific framework: a fluid Euler simulation on a fixed Cartesian mesh coupled to a Lagrangian structural method. The issues posed here are restricted to the fluid component of the calculation. However, test cases have been constructed to demonstrate the capacity of interfacing with the structural calculation. These require calculating solutions to a deforming body on a fixed Cartesian mesh.

The 19 test cases outlined in this document span the range from one-dimensional (1-D) model problems to three-dimensional (3-D) explosion bubble simulations. This document describes each test case, defines the meshes on which it will be solved, prescribes the initial and boundary conditions, and provides reference solutions when possible.

Overview of Test Cases

The test cases are divided into three classes:

1. 1-D fixed boundaries (seven cases),
2. 2-D and 3-D fixed boundaries (eight cases), and
3. Unsteady boundaries (four cases).

The boundaries are fixed throughout the calculation for classes 1 and 2. Additionally, these boundaries are rectangular in shape and coincide with grid lines. The emphasis here is to examine numerical scheme resolution. Class 3 considers cases with moving boundaries that do not coincide with grid lines. Solution of this type problem is necessary to allow coupling to the Lagrangian model. A list of the test cases is provided in Table I.

As is indicated in Table I, there are 19 test cases. However, some of these cases involve multiple calculations using different meshes. Also shown in this table is the maximum number of cells required in each case as well as an estimate of the computational resources needed. The resource figure was arrived at by multiplying the number of cells by the estimated number of computational steps, assuming a CFL safety factor of 0.9.

The test cases contain mixes of the following three different materials: γ law gas, water, and explosive products. The equations of state to be used for these test cases are described in detail below. In cases involving water and explosive products, the units are CGS units (i.e., cm-g-s-dyne).

Benchmark solutions are provided for the test cases wherever possible. These can take the form of closed form solutions or calculations completed on very fine meshes. In other cases, there is no closed form solution and the computational requirements of the problem preclude obtaining a very fine, mesh converged result.

Table I. Test Cases

Problem	Title	No. materials	Maximum cells	Resources (step × cells)
	I. 1-D Fixed Boundaries			
I.A	Single Material Riemann	1	4.00E+02	6.E+04
I.B	Mixed Material Riemann	2	4.00E+02	6.E+04
I.C	Cavitation Shock	1	4.00E+02	4.E+05
I.D	Double Shock Tube	2	1.00E+03	6.E+05
I.E	Spherical Explosion Shock	2	2.00E+03	2.E+06
I.F	Spherical Bubble Collapse	2	1.16E+03	2.E+07
I.G	Mixed Material Expansion	2	4.00E+02	1.E+05
	II. 2-D and 3-D Fixed Boundaries			
II.A	Single Material Riemann in 2-D	1	9.00E+04	1.E+07
II.B	Spherical Explosion Shock in 2-D	2	1.00E+06	5.E+08
II.C	Spherical Bubble Collapse in 2-D	2	8.47E+04	6.E+08
II.D	Spherical Explosion Shock in 3-D	2	5.12E+05	4.E+07
II.E	Bubble Jetting	2	1.75E+05	1.E+09
II.F	Gun Blast	1	2.50E+05	7.E+07
II.G	Steady Channel Flow	1	5.20E+04	N/A
II.H	Free Field Cavitation	3	6.24E+04	2.E+07
	III. Unsteady Boundaries			
III.A	Spherical Piston in 1-D	1	2.50E+02	2.E+04
III.B	Mixed Material Piston	2	1.60E+05	5.E+07
III.C	Bubble Jetting with Moving Plate	2	1.15E+05	3.E+09
III.D	Spherical Piston in 3-D	1	1.25E+05	5.E+06

Equations of State

The test cases involve three different types of materials: γ law gas, explosion products, and water. The equations of state describing these materials are given below.

γ Law Gas: The γ law gas equation of state is given by the equation:

$$p = (\gamma - 1)e\rho, \tag{1}$$

where γ = ratio of specific heats.

Water Equation of State: The equation of state for water is based on the Tait model. To this description a pressure floor has been added to simulate cavitation. The predicted pressure is not allowed to fall below the cavitation pressure, although the density can continue to decrease below its critical value, ρ_c, which produces the cavitation pressure, p_c.

$$p = \begin{cases} B\left(\left(\dfrac{\rho}{\rho_o}\right)^{\gamma} - 1\right) + A & \text{if } \rho > \rho_c, \\ p_c & \text{otherwise} \end{cases} \tag{2}$$

The same values for the constants appearing in this equation are used throughout the test cases:

$\gamma = 7.15$
$A = 1.E+6$ d/cm^2
$B = 3.31E+9$ d/cm^2
$\rho_o = 1.$g/cm^3
$\rho_c = 1.0-4.225E-5$ g/cm^3
$p_c = 220.2726$ d/cm^2.

This formulation leads to a sound speed of zero in cavitated regions since pressure does not change with density variations. Numerically, this may have catastrophic consequences for some schemes, and hence any formula for sound speed in the cavitated regions may be used. One possibility is to use $a_c^2 = a^2(\rho_c)$.

Explosive Products: The explosive products are defined by the Jones-Williams-Lee (JWL) equations of state:

$$p = A\left(1-\frac{\omega\rho}{R_1\rho_o}\right)e^{-R_1\frac{\rho_o}{\rho}} + B\left(1-\frac{\omega\rho}{R_2\rho_o}\right)e^{-R_2\frac{\rho_o}{\rho}} + \omega\rho e \tag{3}$$

The following set of constants is used unless an alternative set is specified:

$A = 5.484E+12$ d/cm^2
$B = 0.09375E+12$ d/cm^2
$R_1 = 4.94$
$R_2 = 1.21$
$\omega = 0.28$
$\rho_o = 1.63$

2. ONE-DIMENSIONAL FIXED BOUNDARIES

I.A Single Material Riemann Problem

Description: A tube contains a γ law gas, $\gamma = 1.4$, in two different states:

State 1: $\rho = 0.002$, $e = 12.25\text{E+9}$, $p = 9.80\text{E+6}$, $u = 0$.
State 2: $\rho = 0.001$, $e = 6.125\text{E+9}$, $p = 2.45\text{E+6}$, $u = 0$.

State 1 occupies the left side of the tube while state 2 occupies the right side. These states are separated by a diaphragm that disappears at $t = 0$, allowing the gas from both sections of the tube to interact. This problem is cast in 1-D Cartesian coordinates. The calculation starts at time $t = 0$ and terminates at $t = 0.0022$ second.

Mesh: Uniform mesh is used with 400 cells and a cell width of $\Delta x = 1$.

Initial Conditions: The initial conditions for the cells are prescribed as follows:

Cells 1–200: state 1
Cells 201–400: state 2.

Boundary Conditions: The computation is terminated before the boundaries can influence the solution.

Benchmark: This problem has an exact, closed form solution.

Output: Compare the calculated solution with the exact solutions of Figures 2.1 to 2.3. These comparisons required pressure, density, and velocity at 2.0E−4, 1.0E−3, and 2.2E−3 seconds.

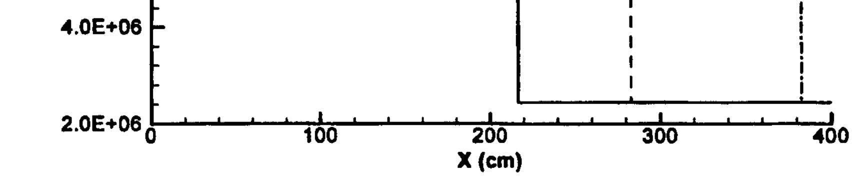


Figure 2.1. Pressure Distribution for Problem I.A

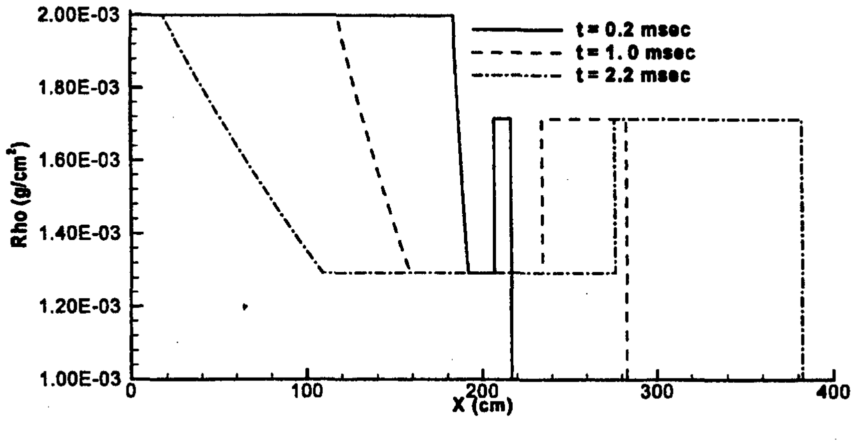


Figure 2.2. Density Distribution for Problem I.A

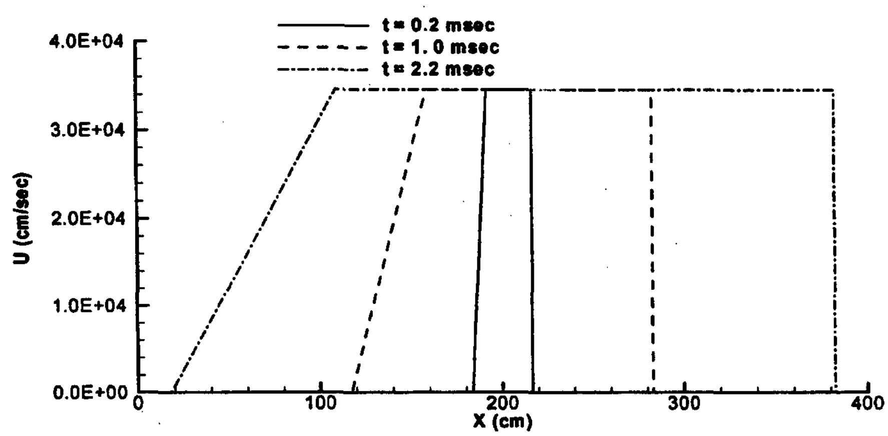


Figure 2.3. Velocity Distribution for Problem I.A

I.B Mixed Material Riemann Problem

Description: A tube contains a JWL gas and water at the following conditions:

JWL material: $\rho = 1.63$, $e = 4.2814\text{E+}10$, $p = 7.81\text{E+}10$, $u = 0$.
Water: $\rho = 1.0$, $e =$ N/A, $p = 1.00\text{E+}6$, $u = 0$.

The JWL material occupies the left side of the tube while water occupies the right side. These materials are separated by a diaphragm which disappears at $t = 0$, allowing the gas from both sections of the tube to interact. This problem is cast in 1-D Cartesian coordinates. The calculation starts at $t = 0$ second and terminates at $t = 0.0005$ second.

Mesh: A uniform mesh is applied with 400 cells and a cell width of $\Delta x = 1$.

Initial Conditions: The initial conditions for the cells are prescribed as follows:

Cells 1–200: JWL material
Cells 201–400: water.

Boundary Conditions: The computation is terminated before the boundaries can influence the solution.

Benchmark: This problem has an exact, closed form solution.

Output: Compare the calculated solution with the exact solutions of Figures 2.4 to 2.6. These comparisons required pressure, density, and velocity data at 1.25E-4, 2.50E-4, and 5.0E-4 seconds.

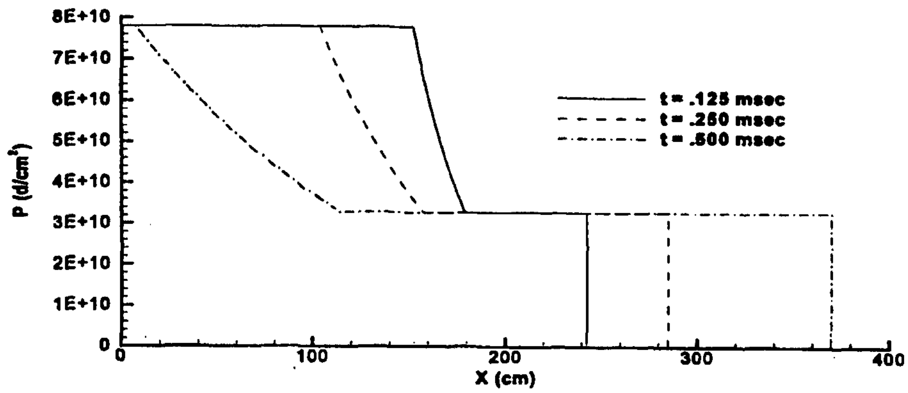


Figure 2.4. Pressure Distribution for Problem I.B

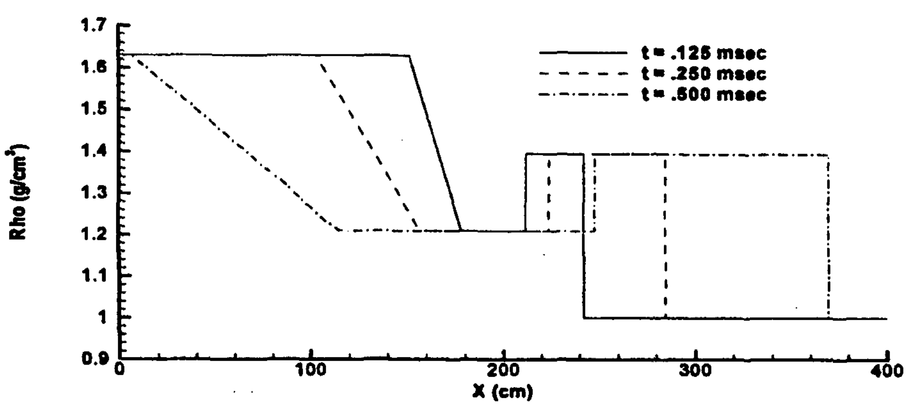


Figure 2.5. Density Distribution for Problem I.B

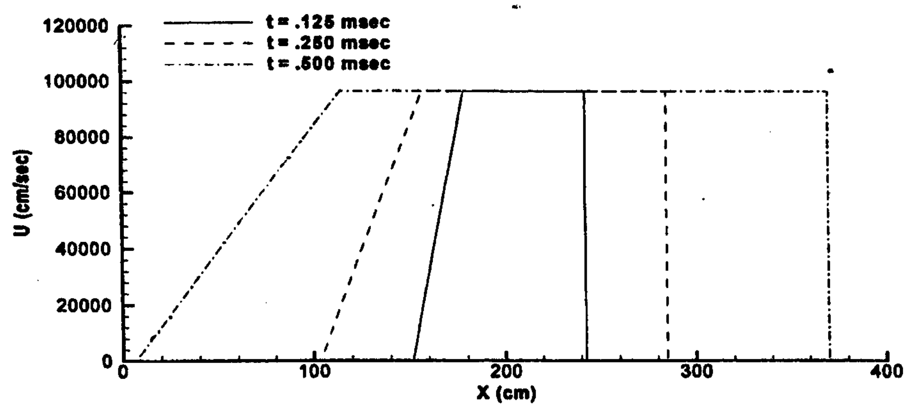


Figure 2.6. Velocity Distribution for Problem I.B

I.C Cavitation Shock

Description: A shock with a density jump of 1.2 travels down a tube of cavitated water with $\rho = 0.99$. A transition from the cavitated state to the water state occurs across the shock. Initial states are

Left (cavitated): $\rho = 0.99$, $e = \text{N/A}$, $p = 220.2726$, $u = 0$.
Right (water): $\rho = 1.001115$, $e = \text{N/A}$, $p = 2.748\text{E}+7$, $u = -555.136719$.

This problem is cast in 1-D Cartesian coordinates. The calculation starts at time $t = 0$ and terminates at $t = 0.006$ second.

Mesh: A uniform mesh is applied with 400 cells and a cell width of $\Delta x = 1$.

Initial Conditions: The initial conditions for the cells are prescribed as follows:

Cells 1–350: left state
Cells 351–400: right state.

Boundary Conditions: The problem terminates before the left boundary can influence the solution. Inflow conditions are applied at the right boundary (i.e., $x = 400$).

Benchmark: This problem has an exact, closed form solution. Solving the mass and momentum conservation relations leads to:

$$\frac{u_2}{u_1} = \frac{(p_2 - p_1)}{(\rho_2 - \rho_1)}$$

Output: Compare the calculated solution with the exact solution of Figures 2.7 to 2.9. Pressure, density, and velocity data are required at 2.E-3, 4.E-3, and 6.E-3 seconds.

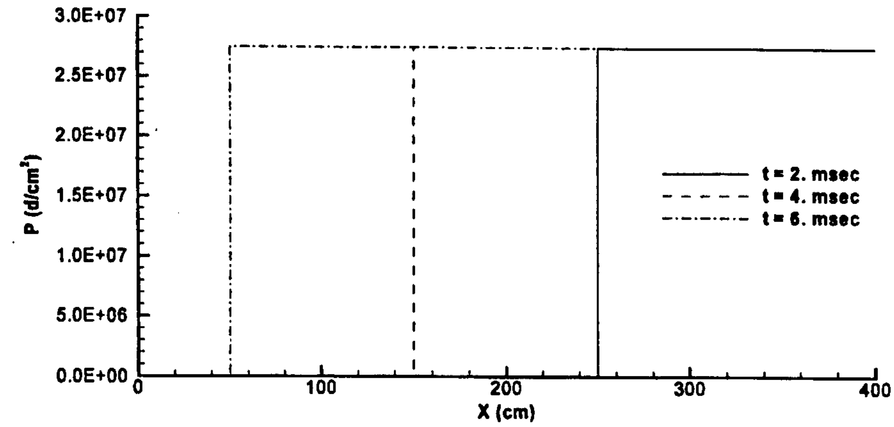


Figure 2.7. Pressure Distribution for Problem I.C

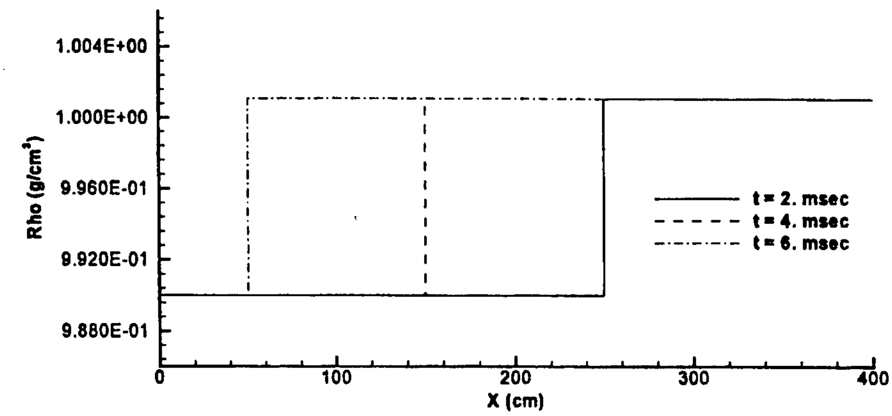


Figure 2.8. Density Distribution for Problem I.C

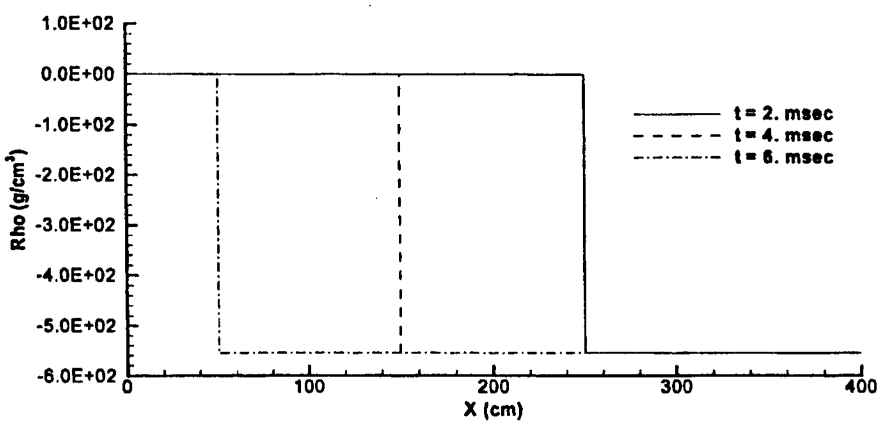


Figure 2.9. Energy Distribution for Problem I.C

I.D Double Shock Tube

Description: A tube, 1,000 cm long and closed at both ends, is filled with two fluids, a γ law gas with γ = 1.25 and water. Initially, the tube contains the following four states:

State	Material	Density	Energy	Pressure	Velocity
1	γ law gas	8.26605505E−3	4.83906770E+10	1.E+8	2.94997131E+05
2	γ law gas	0.001	4.0E+9	1.E+6	0.
3	water	1.0	N/A	1.E+6	0.
4	water	1.0041303	N/A	1.E+8	−6.3813588E+02

This problem is cast in Cartesian coordinates. The computation starts at time $t = 0$ and terminates at $t = 0.003$ second.

Mesh: Complete the calculation on the following three uniform meshes:

1. 250 cells, $\Delta x = 4$
2. 500 cells, $\Delta x = 2$
3. 1,000 cells, $\Delta x = 1$

Initial Conditions: Cell initial conditions for the three meshes are as follows:

Mesh	State 1	State 2	State 3	State 4
1	1–24	25–125	126–240	241–250
2	1–48	49–250	251–480	481–500
3	1–96	97–500	501–960	961–1000

Boundary Conditions: Reflection conditions are applied at the left and right boundaries.

Benchmark: The benchmark is a mesh converged solution with 8,000 cells.

Output: Compare calculations with the benchmark solution of Figures 2.10 through 2.12. These figures require pressure, density, and velocity data at 1.155E−3, 2.00E−3, and 3.00E−3 seconds.

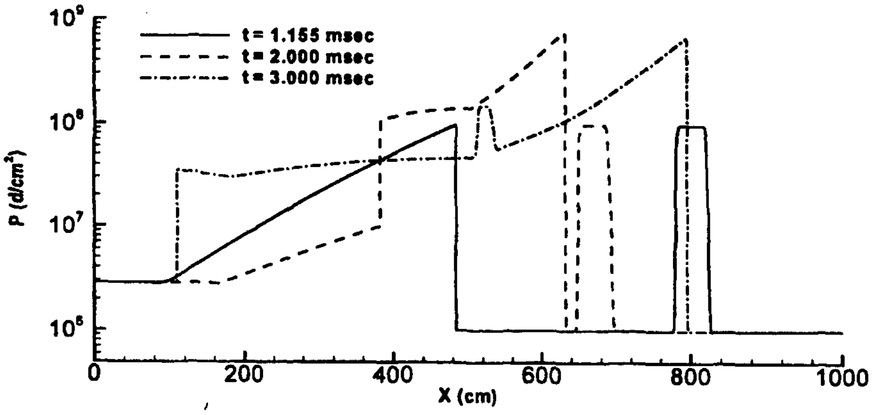


Figure 2.10. Pressure Distribution for Problem I.D

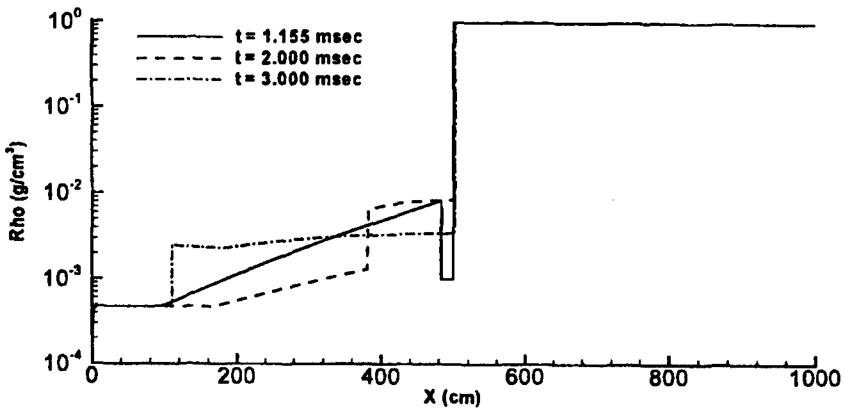


Figure 2.11. Density Distribution for Problem I.D

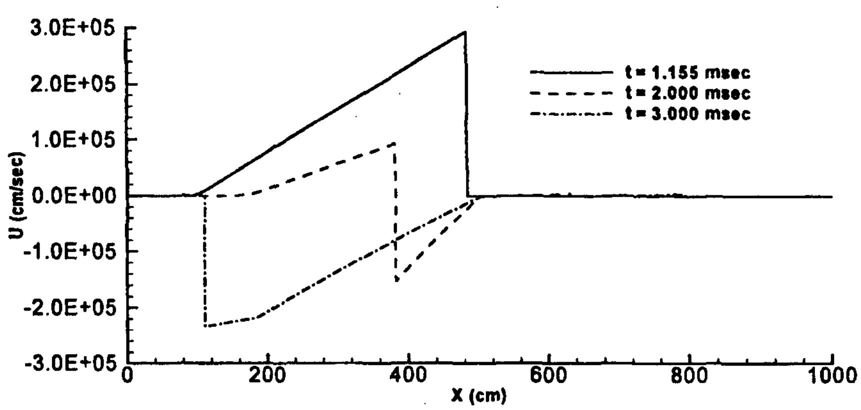


Figure 2.12. Velocity Distribution for Problem I.D

I.E Spherical Explosion Shock

Description: High-pressure JWL material fills a small bubble at the center of a spherical mesh. This bubble, with a radius of 16 cm, is surrounded by water. The initial material states are:

JWL: $\rho = 1.63$, $e = 4.2814\text{E+10}$, $p = 7.8039\text{E+10}$, $u = 0$
Water: $\rho = 1.000$, $e = \text{N/A}$, $p = 1.\text{E+6}$, $u = 0$.

This problem is cast in spherical coordinates. The computation starts at time $t = 0$ and terminates at $t = 0.005$ second.

Mesh: Complete the calculation on the following three uniform meshes:

1. 500 cells, $\Delta x = 2$
2. 1,000 cells, $\Delta x = 1$
3. 2,000 cells, $\Delta x = 0.5$

Initial Conditions: Initial conditions are prescribed as follows for each mesh:

Mesh	JWL	Water
1	1–8	9–500
2	1–16	17–1000
3	1–32	33–2000

Boundary Conditions: The computation is terminated before the outer boundary can influence the solution.

Benchmark: A mesh converged, interface, and shock tracking solution with 1,600 cells is used as the benchmark. This technique eliminates mixed cells and strong shocks from the calculation. The interior of the bubble is modeled with 800 points and the exterior with 799 points.

Output: Compare the calculations with the benchmark solutions of Figures 2.13 through 2.17. These comparisons require data at from the computed solution at 0.5E−3, 1.E−3, 2.E−3, and 3.E−3 seconds. Pressures are compared at the following radial locations: 121, 201, 361, and 525 cm. Impulse is compared at the inner two locations.

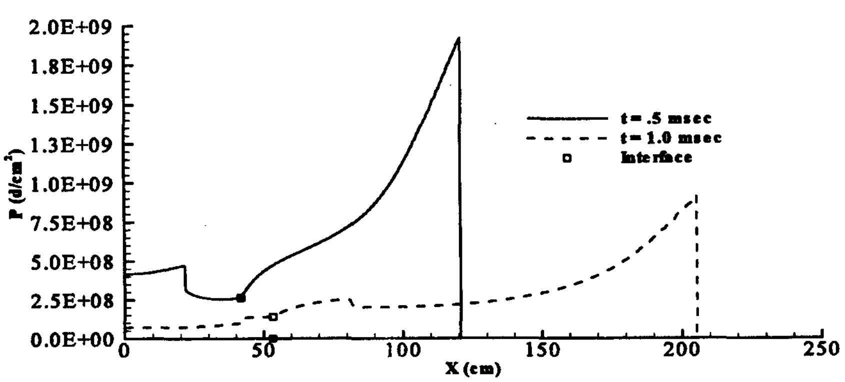


Figure 2.13. Pressure Distribution for Problem I.E at Early Times

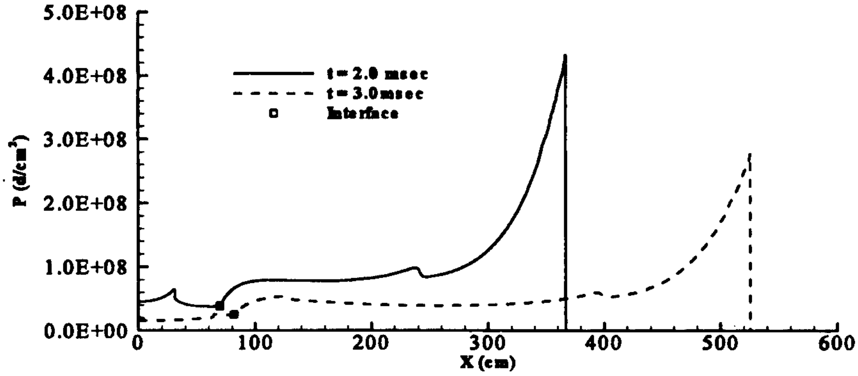


Figure 2.14. Pressure Distribution for Problem I.E at Later Times

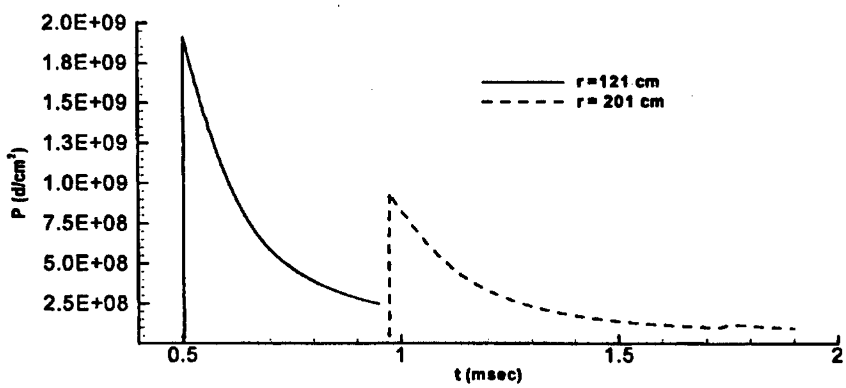


Figure 2.15. Pressure at r = 121 and 201 cm

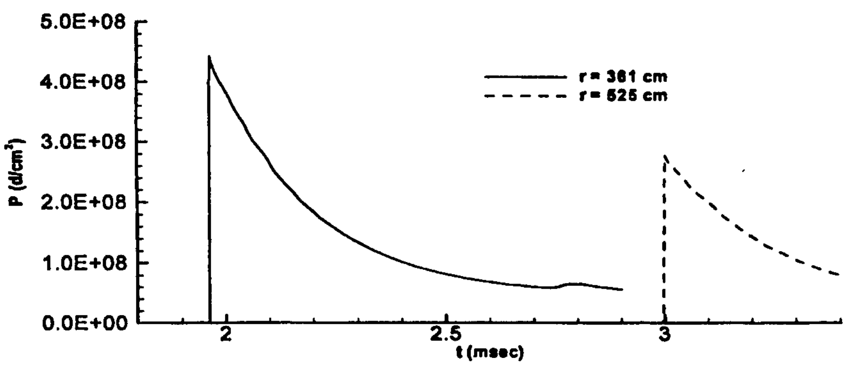


Figure 2.16. Pressure at r = 361 and 525 cm

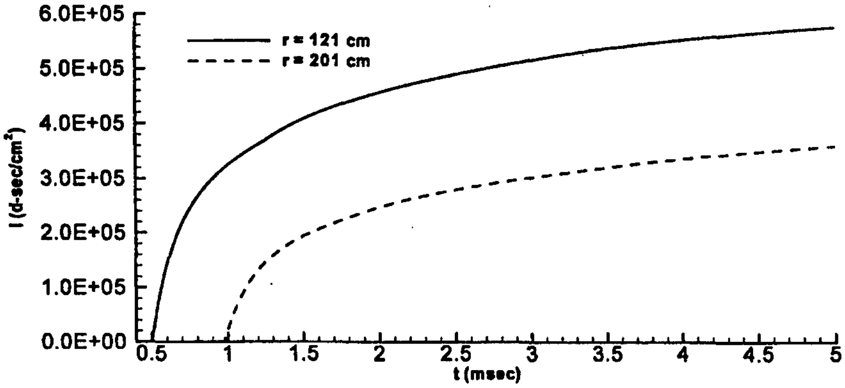


Figure 2.17. Impulse at r = 121 and 201 cm

1.F Spherical Bubble Collapse

Description: A region of high-pressure JWL material fills a small bubble at the center of a spherical mesh. This bubble, with a radius of 16 cm, is surrounded by water, and the calculation is continued through the first bubble collapse. The initial material states for this problem are:

JWL: $\rho = 1.63$, $e = 4.2814\text{E+}10$, $p = 7.8039\text{E+}10$, $u = 0$
Water: $\rho = 1.00037984$, $e = \text{N/A}$, $p = 1.\text{E+}7$, $u = 0$.

This problem is cast in spherical coordinates. The calculation is started at time $t = 0$ and terminates at $t = 0.15$ second.

Mesh: Three different non-uniform meshes are used. Each mesh is broken into two blocks in which the ratio of the widths of adjacent cells are fixed.

Block	No. of cells	Δr_1	Δr_2	$\Delta r_1/\Delta r_2$	Cell No. range
			Mesh 1 (291 cells)		
1	15	2.0	2.0	1.0	1–15
2	276	2.0	474.5612603	1.0200872	16–291
			Mesh 2 (581 cells)		
1	30	1.0	1.0	1.0	1–30
2	551	1.0	238.7280494	1.0100049	31–581
			Mesh 3 (1160 cells)		
1	60	0.5	0.5	1.0	1–60
2	1100	0.5	120.0803306	1.005	61–1160

Initial Conditions: Initial conditions are prescribed as follows for each mesh:

Mesh	JWL	Water
1	1–8	9–291
2	1–16	17–581
3	1–32	33–1160

Boundary Conditions: The computation is terminated before the outer boundary can influence the solution.

Benchmark: A mesh converged, interface tracking solution with 1,589 cells is used as the benchmark. This technique eliminates mixed cells from the calculation. The interior of the bubble is modeled with 1,024 points, while the water expanse is modeled with 565 points.

Output: Compare the calculations with the benchmark solutions of Figures 2.18 through 2.24. These comparisons require pressure and velocity data at 0.0375 t_p, 0.101 t_p, 0.251 t_p, 0.502 t_p, 0.754 t_p, 0.873 t_p, 0.970 t_p, and 1.00 t_p as well as the bubble radius history. Here t_p is the computed time to the minimum bubble volume.

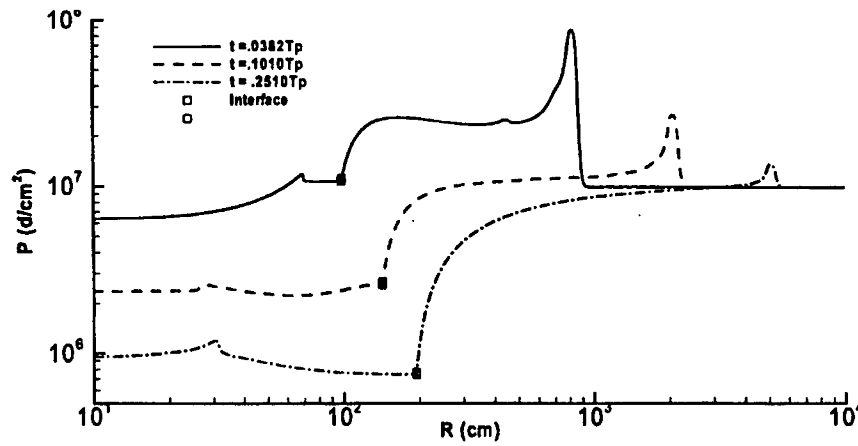


Figure 2.18. Pressure Distribution for Problem I.E at t = 0.0375, 0.101, and 0.251 t_p

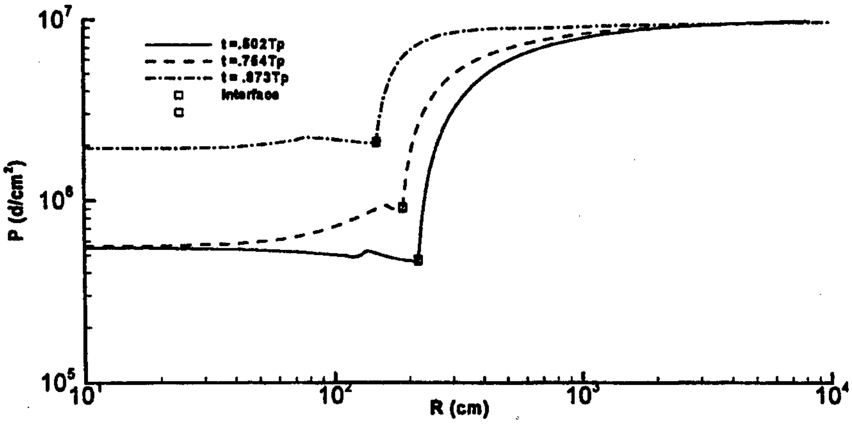


Figure 2.19. Pressure Distribution for Problem I.E at $t = 0.502, 0.754$, and $0.873\ t_p$

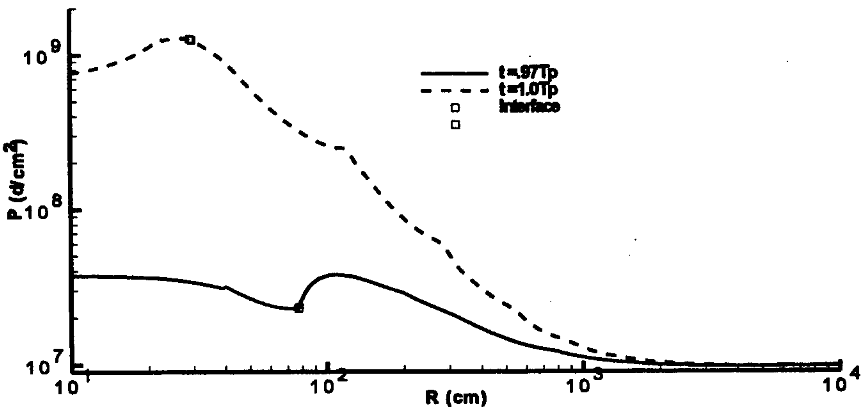


Figure 2.20. Pressure Distribution for Problem I.E at $t = 0.970$ and $1.00\ t_p$

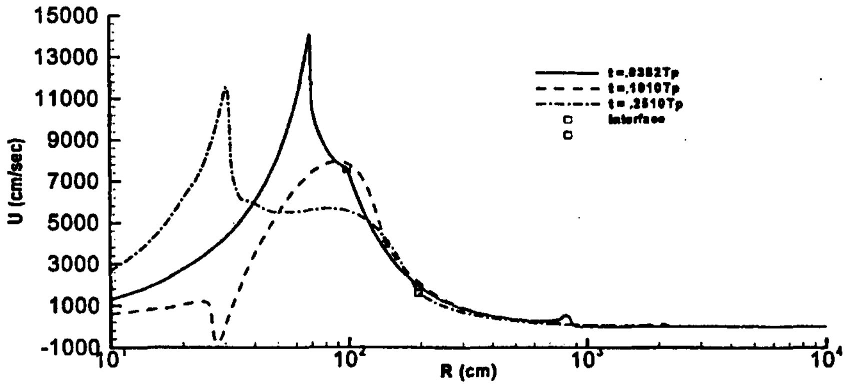


Figure 2.21. Velocity Distribution for Problem I.E at $t = 0.375, 0.101,$ and $0.251\ t_p$

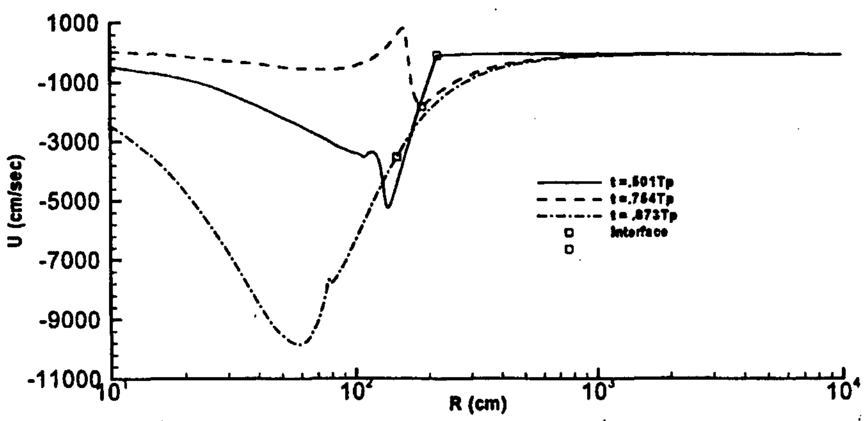


Figure 2.22. Velocity Distribution for Problem I.E at $t = 0.502, 0.754,$ and $0.873\ t_p$

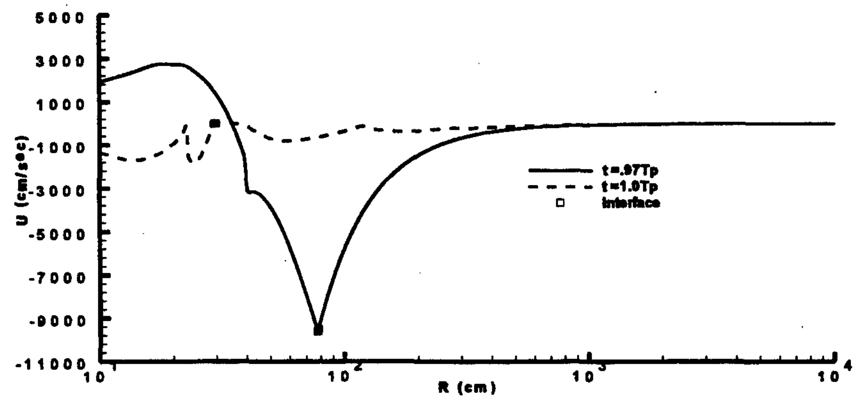


Figure 2.23. Velocity Distribution for Problem I.E at $t = 0.970$ and $1.00\ t_p$

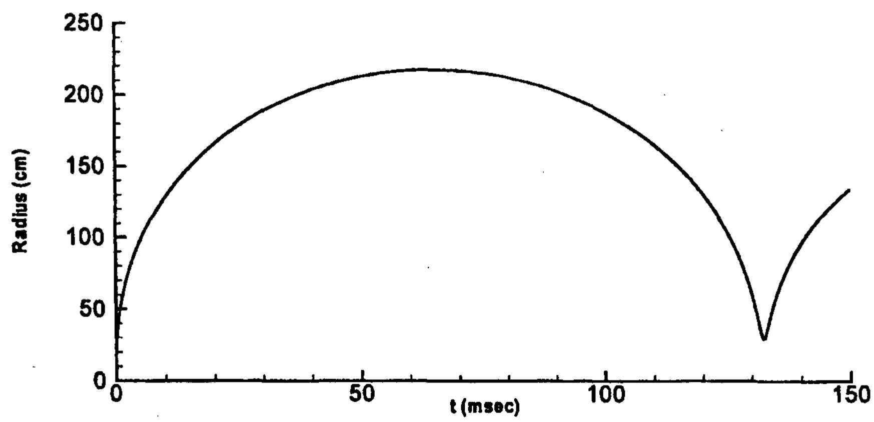


Figure 2.24. Bubble Radius as a Function of Time

I.G Mixed Material Expansion

Description: A fluid is accelerated away from a wall, producing an expansion wave. The fluid consists of a γ law gas with $\gamma = 1.3$ and water. The water is sandwiched between two gas regions. Both gas regions are at the same state, and the two initial states for the problem are

γ law gas: $\rho = 0.035$, $e = 9.5238E+9$, $p = 1.E+8$, $u = 5.E+4$
Water: $\rho = 1.00413030$, $e = N/A$, $p = 1.E+8$, $u = 5.E+4$.

This problem is cast in 1-D Cartesian coordinates. The computation starts at $t = 0$ and terminates at $t = 0.007$ seconds.

Mesh: Run the calculation on the following three uniform meshes:

1. 100 cells, $\Delta x = 10$
2. 200 cells, $\Delta x = 5$
3. 400 cells, $\Delta x = 2.5$

Initial Conditions:

Mesh	No. of cells	Gas	Water
1	100	1–10 & 31–100	11–30
2	200	1–20 & 61–200	21–60
3	400	1–40 & 121–400	41–120

Boundary Conditions: Reflection conditions are applied at the left boundary. Outflow occurs at the right boundary.

Benchmark: The benchmark is a mesh converged solution with 5,000 points.

Output: Compare the calculations with the benchmark of Figures 2.25 through 2.27. These comparisons require data at 1.5E-3, 2.5E-3, and 7.0E-3 seconds.

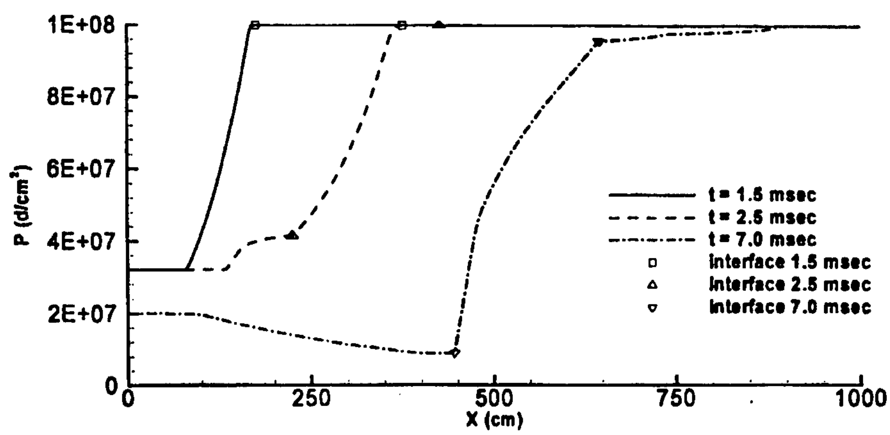


Figure 2.25. Pressure Distribution for Problem I.G

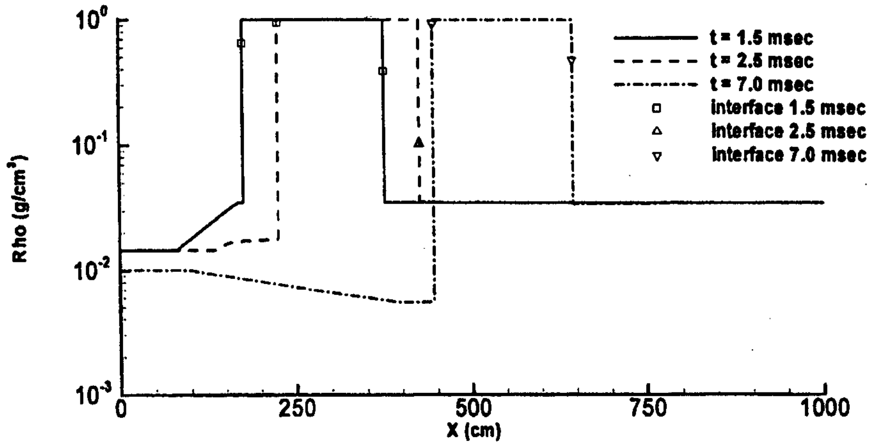


Figure 2.26. Density Distribution for Problem I.G

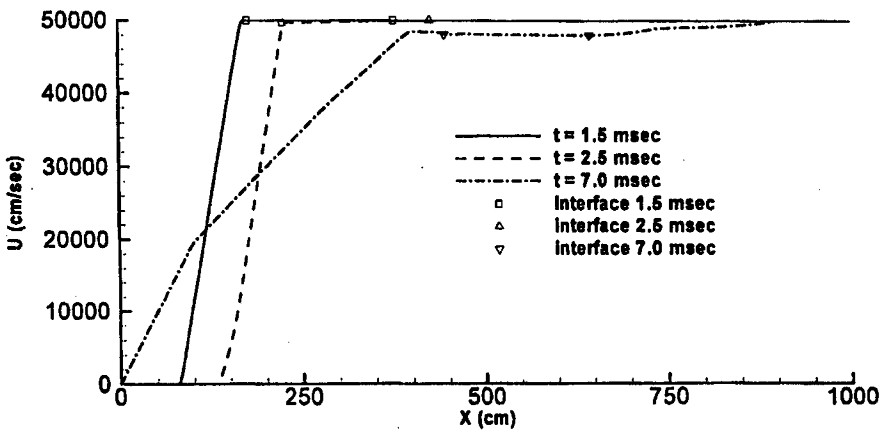


Figure 2.27. Velocity Distribution for Problem I.G

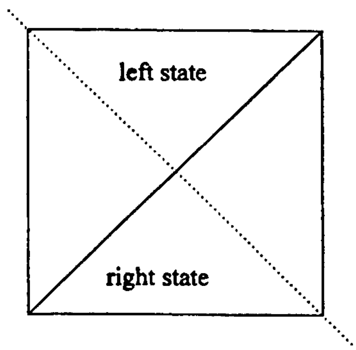
3. TWO-DIMENSIONAL AND THREE-DIMENSIONAL FIXED BOUNDARIES

II.A Single Material Riemann Problem in 2-D

Description: A square computational domain, containing a γ law gas with $\gamma = 1.4$, is divided into two regions along the diagonal as is shown in the sketch. The regions contain the two states defined below:

Left: $\rho = 0.002$, $e = 12.25E+9$, $p = 9.80E+6$, $u = 0$.
Right: $\rho = 0.001$, $e = 6.125E+9$, $p = 2.45E+6$, $u = 0$.

This problem is cast in 2-D planar coordinates. This problem starts at time $t = 0$ and terminates a $t = 2.2E-3$ seconds.



Mesh: The mesh is 2-D with 300 uniform cells of width $\Delta x = 1$ in each direction.

Boundary Conditions: Boundaries do not influence the centerline for the duration of the problem.

Initial Conditions: Initial properties are assigned as follows:

	Left state	Right state
1	1	2–300
2	1–2	3–300
3	1–3	4–400
.	.	.
.	.	.
.	.	.
299	1–299	300
300	1–300	

Benchmark: This problem has the same solution of I.A.

Output: Compare the calculated solution along the second diagonal (dotted line in sketch) with the exact solutions of Figures 3.1 to 3.3. Target times for these comparisons are 2.0E−4, 1.0E−3, and 2.2E−3 seconds.

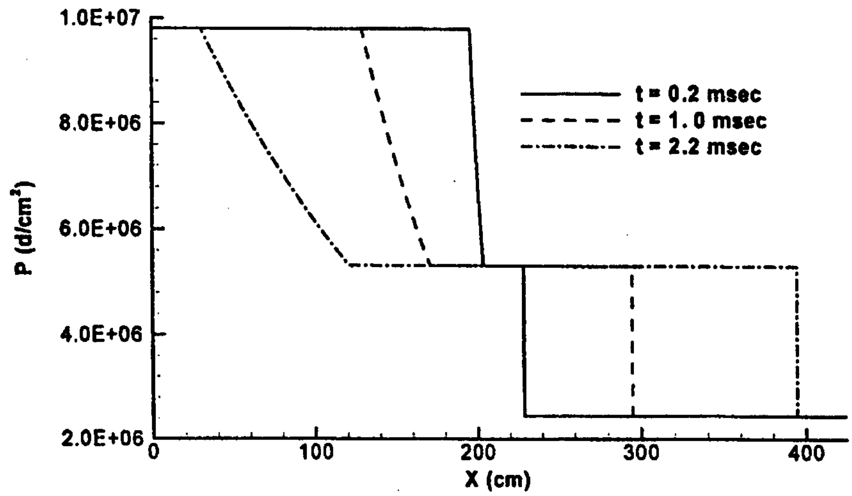


Figure 3.1. Pressure Distribution From Problem II.A

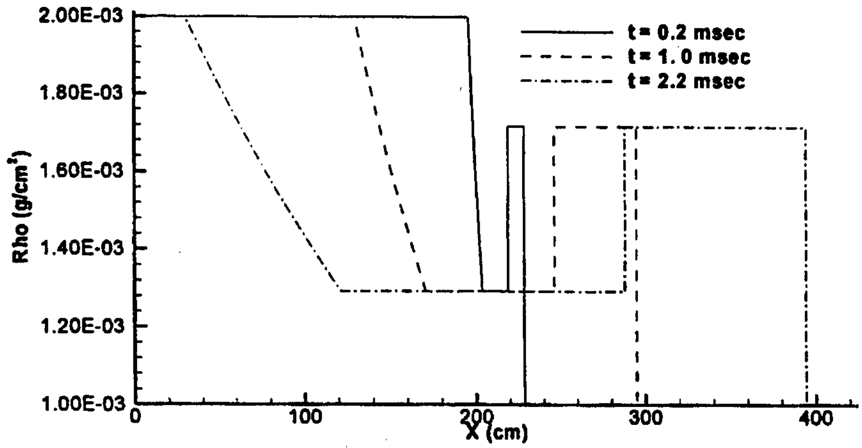


Figure 3.2. Density Distribution From Problem II.A

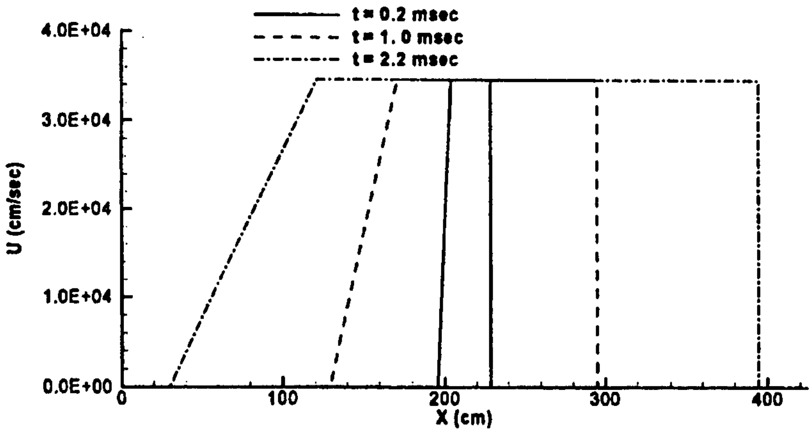


Figure 3.3. Velocity Distribution From Problem II.A

II.B Spherical Explosion Shock in 2-D

Description: High-pressure JWL material, with a radius of 16 cm, fills a small bubble in a uniform pressure, water-filled flow field. The initial material states for this problem are

JWL: $\rho = 1.63$, $e = 4.2814E+10$, $p = 7.8039E+10$, $u = 0$
Water: $\rho = 1.000$, $e = N/A$, $p = 1.E+6$, $u = 0$.

This problem is cast in 2-D cylindrical coordinates. As is indicated in Figure 3.4, the mesh covers only the top half of the problem and the JWL gas is located at the lower left corner of the computational region. This problem is started at time $t = 0$ and terminates at $t = 5.E-3$ second.

Mesh: Two different uniform meshes are used:

1. r direction: 500 cells, $\Delta r = 2.$, z direction: 500 cells, $\Delta z = 2$

2. r direction: 1,000 cells, $\Delta r = 1.$, z direction: 1,000 cells, $\Delta z = 1$.

Initial Conditions: All cells initially contain water except for those listed below, which are filled with JWL gas:

Mesh 1		Mesh 2	
i-indices	*k-indices*	*i-indices*	*k-indices*
1 to 8	1 to 4	1 to 16	1 to 8
1 to 6	5 to 6	1 to 12	9 to 12
1 to 3	7 to 7	1 to 6	13 to 14
1 to 1	8 to 8	1 to 2	15 to 16

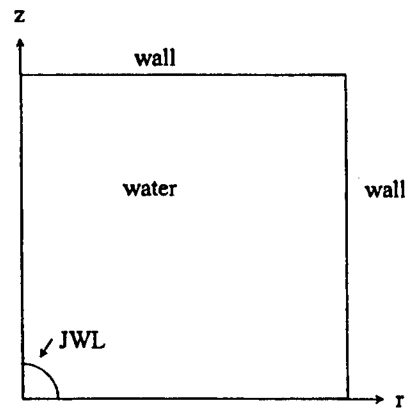


Figure 3.4 Sketch of Problem II.B and II.C

Boundary Conditions: Reflection condition are applied to boundaries.

Benchmark: Same as case I.E

Output: Compare the calculations with the benchmark solutions of Figures 2.13 through 2.17. These comparisons require the computed data field at the times 0.5E-3, 1.E-3, 2.E-3, and 3.E-3 seconds. Pressures histories are compared at the following radial locations: 121, 201, 361, and 525 cm. Impulse histories are compared at the inner two locations.

A concern in evaluating the results of this test is accessing the symmetry of the solution. Hence, all comparisons should include three solutions: along the x axis, the z axis, and the diagonal.

II.C Spherical Bubble Collapse in 2-D

Description: A region of high-pressure JWL gas, with a radius of 16 cm, fills a small bubble at the lower left corner of a 2-D, cylindrical mesh as shown in Figure 3.4. This bubble is surrounded by water, and the calculation is continued through the first bubble collapse. The initial material states for this problem are

JWL: $\rho = 1.63$, $e = 4.2814E+10$, $p = 7.8039E+10$, $u = 0$
Water: $\rho = 1.00037984$, $e = N/A$, $p = 1.E+7$, $u = 0$.

This problem is cast in 2-D cylindrical coordinates, starts at $t = 0$, and terminates at t = 0.15 second.

Mesh: The mesh consists of 291 points in the r direction and 291 points in the z direction (see Figure 3.4). In each direction, the mesh is broken into two blocks in which the ratio of the widths of adjacent cells is fixed.

Mesh blocks in the r and z directions

Block	*No. of cells*	Δw_{1st}	Δw_{last}	$\Delta w_{i+1}/\Delta w_i$	*Cell No. range*
1	15	2.0	2.0	1.0	1–15
2	276	2.0	474.5612603	1.0200872	16–291

Boundary Conditions: The boundaries do not influence the solution for the duration of the problem.

Initial Conditions: All cells contain water at the initial condition except for those listed below, which are filled with JWL gas at the initial conditions:

Mesh 1

i-indices	*k-indices*
1 to 8	1 to 4
1 to 6	5 to 6
1 to 3	7 to 7
1 to 1	8 to 8

Benchmark: Same benchmark as is in case I.F.

Output: Compare the calculations with the benchmark solutions of Figures 2.18 to 2.24. These comparisons require pressure and velocity data at 0.0375 t_p, 0.101 t_p, 0.251 t_p, 0.502 t_p, 0.754 t_p, 0.873 t_p, 0.970 t_p, and 1.00 t_p as well as the bubble radius history. Here t_p is the computed time to the minimum bubble volume, and the bubble radius is its effective radius: $r = [(\text{bubble volume})3/(4\pi)]^{1/3}$.

A concern in evaluating the results of this test is accessing the symmetry of the solution. Hence, all comparisons, except the bubble radius, should include three solutions; along the x axis, the z axis, and the diagonal.

II.D Spherical Explosion Shock in 3-D

Description: High-pressure JWL gas, with a radius of 16 cm, is surrounded by water. The initial material states for this problem are:

JWL: $\rho = 1.63$, $e = 4.2814\text{E+}10$, $p = 7.8039\text{E+}10$, $u = 0$
Water: $\rho = 1.000$, $e = \text{N/A}$, $p = 1.\text{E+}6$, $u = 0$.

This problem is cast in 3-D Cartesian coordinates. To reduce the size of the problem, the domain is restricted to the region $x \geq 0, y \geq 0, z \geq 0$, and symmetry conditions are prescribed on the planes: $x = 0$, $y = 0$, $z = 0$. Within this region, the bubble is located in the neighborhood of (0,0,0), as shown in Figure 3.5. The problem is started at time $t = 0$ and is terminated at $t = 0.95\text{E}-3$ seconds.

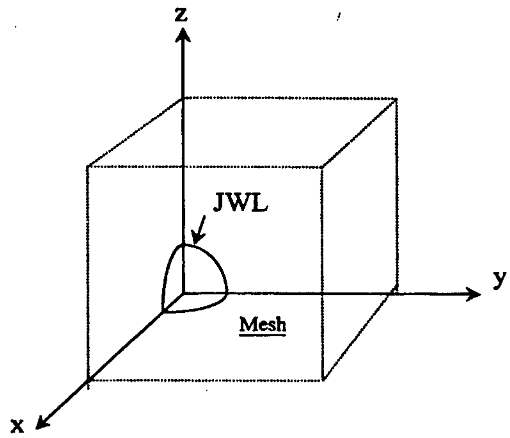


Figure 3.5. Sketch of Problem II.D

Mesh: The mesh is uniform with 100 cells in each direction. The width of the cells are $\Delta x = \Delta y = \Delta z = 2$.

Boundary Conditions: Reflection condition are applied to all boundaries.

Initial Conditions: All cells contain water at the initial condition except for those listed below, which are filled with JWL gas at the initial conditions:

	Mesh 1	
i-indices	*j-indices*	*k-indices*
1–6	1–6	1–6
1–4	1–4	7–7
1–1	1–1	8–9
7–7	1–4	1–4
8–8	1–1	1–1
1–4	7–7	1–4
1–1	8–8	1–1

Benchmark: Same as case I.E

Output: Compare the calculations with the benchmark solutions of Figures 3.6 through 3.8. These comparisons require computed pressures at time 0.5E−3 second, while pressures and impulse histories are compared at a radial distance of 121 cm from the bubble center.

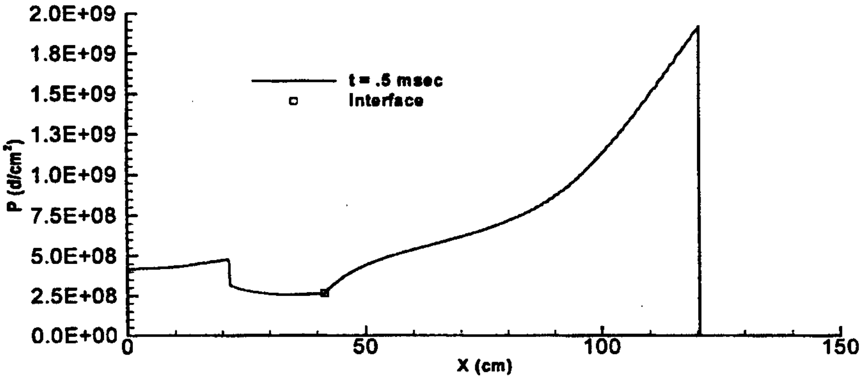


Figure 3.6. Pressure Distribution for Problem II.D

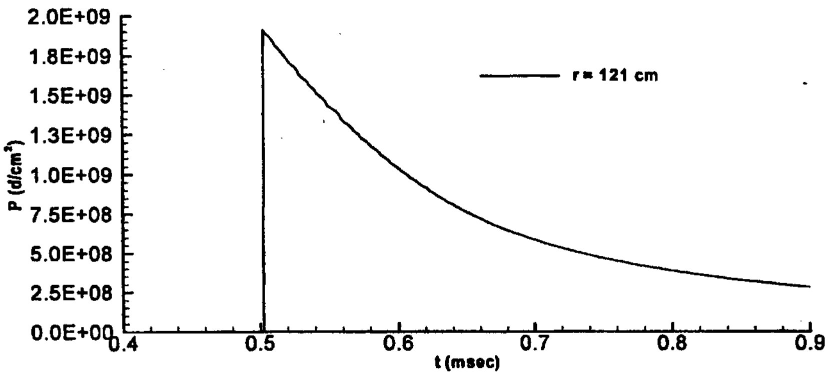


Figure 3.7. Pressure History for Problem II.D

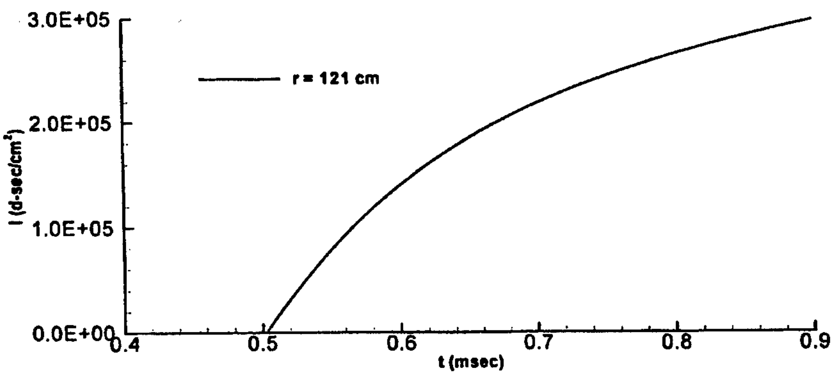


Figure 3.8. Impulse History for Problem II.D

A concern with this case is symmetry solution. Accordingly, the following seven comparisons should be made with the results in Figure 3.6: ($x = y = 0$), ($x = z = 0$), ($y = z = 0$), ($x = y$, $z = 0$), ($x = z$, $y = 0$), ($y = z$, $x = 0$), and ($x = y = z$). Similarly, when comparing history results to Figures 3.7 and 3.8, include data at the following cells: (61,1), (1,61,1), (1,1,61), (44,44,1), (44,1,44), (1,44,44), and (35,35,35).

II.E Bubble Jetting

Description: An explosive device weighing 17.08 grams and located below a flat plat is detonated at a depth of 98.5 meters. A diagram of this problem is shown in Figure 3.9. The plate is circular with a radius of 88.9 cm and has a thickness of 2.54 cm. The initial material states for this problem are:

JWL: $\rho = 1.63$, $e = 4.2945E{+}10$, $p = 8.3837E{+}10$, $u = 0$
Water: $\rho = 1.00039080$, $e =$ N/A, $p = 1.026E{+}7$, $u = 0$.

Note that the water initial state corresponds to a depth of 98.5 meters. As a consequence of gravity, the water density decreases linearly to 1 at the surface.

This problem is cast in 2-D cylindrical coordinates and uses a gravitational constant of 981 cm/s^2. The JWL constants applicable to this problem are $A = 3.712E{+}12$, $B = 0.03231E{+}12$, $\omega = 0.3$, $R_1 = 4.15$, $R_2 = 0.95$, and $\rho_0 = 1.63$ g/cm^3.

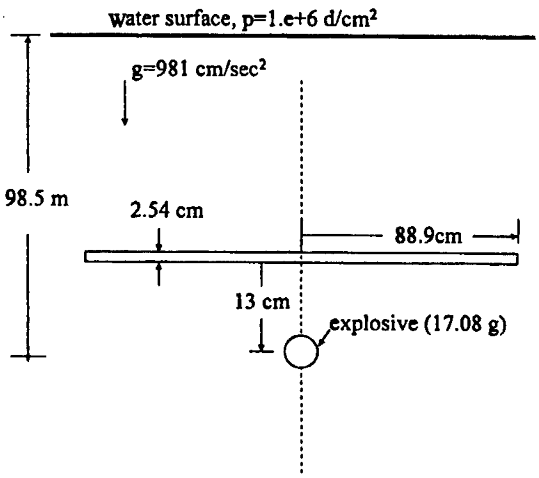


Figure 3.9. Sketch of Problem II.E

Mesh: This computation is done on three different non-uniform meshes. In each case, multiple blocks are used in the r and z direction. Within each block, the ratio of cell widths is constant.

MESH 1

r block

Block	*No. of cells*	Δr_{1st}	Δr_{last}	$\Delta r_{i+1}/\Delta r_i$	*Block width*
1	30	0.8666000	0.8666000	1.0000000	25.9980000 center-line
2	19	0.9099300	2.4956169	1.0576519	30.0000000
3	13	2.6952662	7.2014618	1.0853461	60.0000000
4	18	8.6417541	216.0178141	1.2084500	1,210.8657872 outer edge
	sum: 80				1,326.8637872

z block

Block	*No. of cells*	Δz_{1st}	Δz_{last}	$\Delta z_{i+1}/\Delta r_i$	*Block width*
1	16	239.1976160	9.9444169	0.8089497	1,210.0000000 bottom
2	12	8.1363329	2.7375489	0.9057199	60.0000000
3	19	2.4936169	0.9110406	0.9455968	30.0000000
4	45	0.8666000	0.8666000	1.0000000	38.9970000
5	12	0.9099300	1.6576371	1.0560394	15.0000000
6	10	1.8234008	4.5395182	1.1066599	30.0000000
7	21	5.4519614	212.5264157	1.2010000	1,242.7475815 top
	sum: 135				2,626.7445815

MESH 2

r block

Block	No. of cells	Δr_{1st}	Δr_{last}	$\Delta r_{i+1}/\Delta r_i$	Block width
1	60	0.4333000	0.4333000	1.0000000	25.9980000 center-line
2	40	0.4441325	1.1677330	1.0250968	30.0000000
3	27	1.2144424	3.6515117	1.0432498	60.0000000
4	36	4.0166629	113.9466213	1.1002962	1,210.0000000 outer edge
	sum: 163				1,325.9980000

z block

Block	No. of cells	Δz_{1st}	Δz_{last}	$\Delta z_{i+1}/\Delta r_{zi}$	Block width
1	35	115.9159143	4.2581130	0.9073948	1,210.0000000 bottom
2	26	3.8710079	1.2223771	0.9549382	60.0000000
3	40	1.1679165	0.4441324	0.9755136	30.0000000
4	90	0.4333000	0.4333000	1.0000000	38.9970000
5	24	0.4441325	0.8470602	1.0284694	15.0000000
6	20	0.8894132	2.3251964	1.0518798	30.0000000
7	40	2.5577160	118.7093678	1.1034030	1,242.0000000 top
	sum: 275				2,625.9970000

MESH 3

r block

Block	No. of cells	Δr_{1st}	Δr_{last}	$\Delta r_{i+1}/\Delta r_i$	Block width
1	120	0.2166500	0.2166500	1.0000000	25.9980000 center-line
2	80	0.2193581	0.5900395	1.0126039	30.0000000
3	50	0.6047905	2.0877910	1.0256077	60.0000000
4	68	2.1921805	60.5621060	1.0507812	1,210.0000000 outer edge
	sum: 318				1,325.9980000

z block

Block	No. of cells	Δz_{1st}	Δz_{last}	$\Delta z_{i+1}/\Delta r_{zi}$	Block width
1	68	60.5619219	2.1921597	0.9516728	1,210.0000000 bottom
2	50	2.0877690	0.6047993	0.9750322	60.0000000
3	80	0.5900482	0.2193591	0.9875529	30.0000000
4	180	0.2166500	0.2166500	1.0000000	8.9970000
5	49	0.2193581	0.4128583	1.0132621	15.0000000
6	41	0.4231797	1.1586150	1.0254993	30.0000000
7	81	1.2165457	60.3045612	1.0500024	1,242.0000000 top
	sum: 549				2,625.9970000

The index numbering convention places the point $i = 1, k = 1$ on the bottom of the mesh at the centerline.

Boundary Conditions: The outer radial and the top boundaries are not of influence for the duration of the problem. The bottom boundary must be reflective to counter the effect of gravity.

Initial Conditions: All cells contain water in the initial state except for the following blocks of cells, which are filled with JWL gas at the initial state:

i-index	k-index	Volume fraction JWL material
	Mesh 1	
1-1	79-79	1.0
1-2	78-78	1.0
1-1	77-77	0.125
	Mesh 2	
1-2	164-164	1.0
1-3	160-163	1.0
1-1	159-159	1.0
	Mesh 3	
1-4	323-324	1.0
1-6	315-322	1.0
1-2	313-314	1.0

Note that the density and pressure of water increases with depth due to hydrostatic pressure.

Benchmark: There is not a reliable benchmark for this problem. An experiment similar to this case has been run. However, the plate experienced deflection and motion, and these measurements cannot be used for Euler code verification. Based on this test and other numerical simulations, the following qualitative results are expected:

- The maximum bubble radius is approximately 18 cm.
- Bubble collapse occurs between 0.012 to 0.014 second.
- The bubble jets upwards towards the plate.
- Peak centerline pressures during jetting are of the order of 0.5E+9 to 1.E+9 d/cm^2.
- At $r = 5$ cm, the peak pressure levels drops to half this value.

Output: For each grid show the following:

1. Average bubble radius history. The bubble radius is calculated from

$$r = \left(\frac{3V}{4\pi}\right)^{1/3}$$

where V is the volume of the JWL material.

2. Plate force history (F_p) as a function of time. Here

$$F_p(t) = 2\pi\int_0^R (p_t(r,t) - p_b(r,t))r\,dr,$$

where p_t, p_b are the pressures on the top and bottom of the plate and R is the plate radius.

3. Plate impulse history (I_p) where

$$I_p(t) = \int_0^t F_p(\tau)d\tau.$$

4. Pressure histories at $r = 0$, 2.54, 5.08, 7.62, 10.16, and 12.70 cm for the complete run ($0 < t < 0.015$).

5. Pressure histories at $r = 0$, 2.54, 5.08, 7.62, 10.16, and 12.70 cm during jetting (e.g. $0.012 < t < 0.015$).

6. Impulse histories at $r = 0$, 2.54, 5.08, 7.62, 10.16, and 12.70 cm for the complete run ($0 < t < 0.015$).

7. Pressure contour (or color flood) plots at 0.0375 t_p, 0.102 t_p, 0.251 t_p, 0.502 t_p, 0.754 t_p, 0.873 t_p, 0.970 t_p, 1.00 t_p, and 1.05 t_p, where t_p is the time to minimum volume. The viewing area should be reflected about the original center of the charge to produce a complete image of the bubble. Each contour plot should be centered on the explosive and should cover a square region 100 cm on a side.

II.F Gun Blast

Description: A region of high-pressure γ law gas, $\gamma = 1.4$, partially fills a short gun barrel. The remainder of the barrel and the surrounding area is filled with the same gas at a lower pressure as shown in Figure 3.10. The high- and low-pressure states are:

High-pressure air: $\rho = 0.129$, $e = 1.96317\text{E+}10$, $p = 1.013\text{E+}9$
Ambient air: $\rho = 0.00129$, $e = 1.96317\text{E+}9$, $p = 1.013\text{E+}6$.

This problem is cast in 2-D cylindrical coordinates. It starts at time $t = 0$ and terminates at $t = 1.\text{E}-4$ second.

Mesh: Compute this problem on the following uniform meshes:

Mesh	No. of Cells r direction	No. of Cells z direction	Δr	Δz
1	90	180	0.1	0.1
2	180	360	0.05	0.05
3	360	720	0.025	0.025

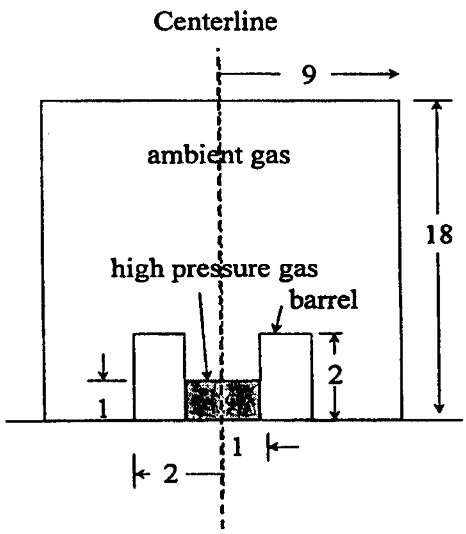


Figure 3.10. Sketch of Problem II.F

Boundary Conditions: Reflection conditions are applied to all boundaries.

Initial Conditions: All cells contain air at the ambient conditions except those indicated on the chart below, which contain air in the high-pressure state.

Mesh	i-indices	k-indices
1	1–10	1–10
2	1–20	1–20
3	1–40	1–40

Benchmark: None

Output: Display the following results:

1. Pressure along the cell column closest to the centerline for all three meshes at 2.5E-5, 5.0E-5, and 1.0E-4 seconds.

2. Pressure along the row of cells closest to line $z = 2.05$ for all three meshes at 2.5E-5, 5.0E-5, and 1.0E-4 seconds.

3. Density contour or color flood plots for the computational domain at 2.5E-5, 5.0E-5, and 1.0E-4 seconds. These figures should span the density range of 0.5E-4 to 0.1.

II.G Steady State Flow in a Channel

Description: A γ law gas, $\gamma = 1.4$, flows through a channel with a forward facing step. The ambient flow condition in the channel is:

$\rho = 0.00129$, $e = 1.96317\text{E+9}$, $p = 1.013\text{E+6}$, $u = 1.\text{E+5}$, Mach = 3.01

The dimensions of the channel are shown in Figure 3.11. This problem is cast in 2-D Cartesian coordinates and is run until convergence to a steady state is achieved. It is not necessary to converge to a steady state in a time-accurate fashion.

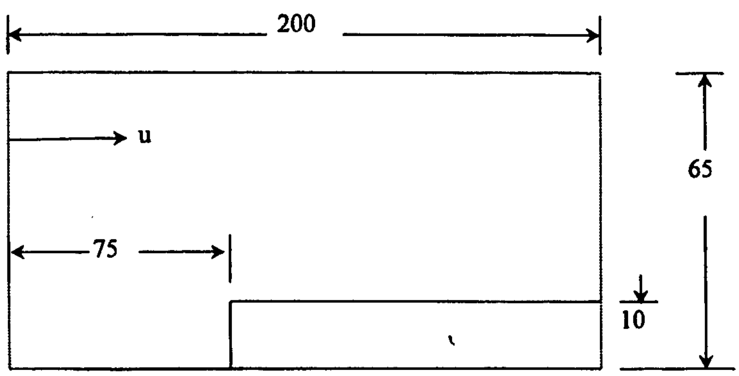


Figure 3.11. Sketch of Problem II.G

Mesh: Compute this problem using the following meshes:

Mesh	No. of cells			
	r direction	Δr	z direction	Δz
1	200	1.0	65	1.0
2	400	0.5	130	0.5

Initial Conditions: All cells are assigned the ambient channel conditions.

Boundary Conditions: The top and bottom boundaries are reflective, while the left is supersonic inflow and the right is supersonic outflow.

Benchmark: There is no benchmark for this problem.

Output:

1. Provide a graph showing the rate of convergence for the meshes. The dependent variable is the number of times steps, while the independent variable is some measure of convergence, such as

$$\frac{\left|\rho_{i,j}^{n} - \rho_{i,j}^{n-1}\right|_{\max}}{\rho_{\max}}$$

Here the maximum values in the numerator and denominator are independently taken over all points in the computation.

2. Plot upper and lower surface pressure as a function of wetted distance from the inflow boundary.

3. Construct density contour or color floods and velocity vector plots of the converged flow field. Two plots should be provided: the first covers the entire flow field, while the second zooms in on a square region, 20 cm on a side. The upper edge of the smaller region is the upper wall, while the horizontal location is adjusted to center of the wall-shock interaction. Both plots span the density range 4.E-4 to 8.E-3.

II.H Free Field Cavitation

Description: An explosive weighing 500 kg is detonated at a depth of 20 meters in open water 200 meters deep. A γ law gas with $\gamma = 1.4$ is used to describe the air above the water. Figure 3.12 depicts the situation. The initial states for this problem are

Air: $\rho = 0.00129$, $e = 1.96317\text{E+9}$, $p = 1.103\text{E+6}$, $u = 0$
Water (depth of 20 m): $\rho = 1.00008343$, $e = \text{N/A}$, $p = 2.975\text{E+6}$, $u = 0$
JWL: $\rho = 1.63$, $e = 4.294479\text{E+10}$, $p = 4.2945\text{E+10}$, $u = 0$

This problem is cast in 2-D cylindrical coordinates. The calculation is started at the time $t = 0$ and is terminated at $t = 0.13$ second, and gravity is taken into account. The JWL constants applicable to this problem are: $A = 3.712\text{E+12}$, $B = 0.0321\text{E+12}$, $\omega = 0.3$, $R_1 = 4.15$, $R_2 = 0.95$, and $\rho_o = 1.63$ g/cm^3.

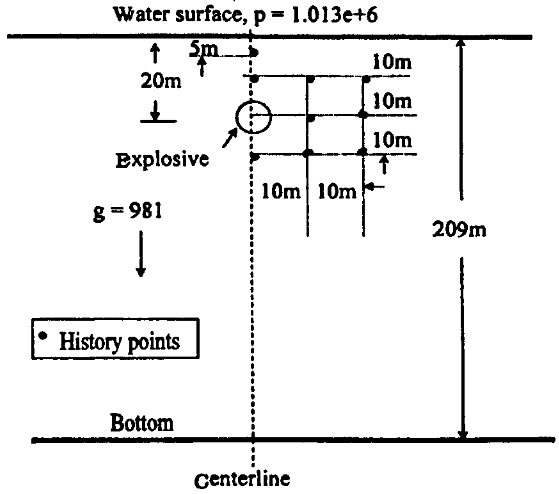


Figure 3.12. Sketch of Problem II.H

Mesh: A 210 by 297 non-uniform mesh is used with the following characteristics:

***r* block**

Block	*No. of cells*	Δr_{1st}	Δr_{last}	$\Delta r_{i+1}/\Delta r_i$	*Block width*
1	70	29.0	29.0	1.0000	2,030 center-line
2	52	29.0	49.74742	1.0106378	2,000
3	88	50.9911	442.0749704	1.0251363	16,000 outer boundary
	sum: 210				20,030

***z* block**

Block	*No.of cells*	Δz_{1st}	Δz_{last}	$\Delta z_{i+1}/\Delta r_{zi}$	*Block width*
1	87	454.255696	49.9058893	0.9746465	16,000 bottom
2	52	49.3971634	29.2929293	0.9898063	2,000
3	100	29.0000	29.0000	1.0000	2,900
4	15	29.29	37.7882193	1.0183631	500
5	43	38.7328248	113.685583	1.0259683	3,000 top
	sum: 297				24,400

Boundary Conditions: The bottom boundary is reflective to counter the hydrostatic pressure. The remaining boundaries do not influence the solution throughout the duration of the problem.

Initial Condition: The cells are initially assigned the following material:

Material	**i-index**	**k-index**
Water	$1 \le i \le 210$	$1 \le k \le 239$
Air	$1 \le i \le 210$	$240 \le k \le 297$
JWL	$i = 1$	$170 \le k \le 171$

Benchmark: None

Output:

1. Construct a graph showing the cavitated volume in the flow field as a function of time.

2. Plot the pressure history of the points indicated on Figure 3.12.

3. Display a pressure contour or color flood plots that also show the boundary of the cavitated region at the following times: 0.015, 0.025, 0.055, 0.095, 0.105, and 0.130 msec.

4. UNSTEADY BOUNDARIES

III.A Spherical Piston in 1-D

Description: A γ law gas with $\gamma = 7$ is displaced radially outwards by a spherical piston, which moves at a prescribed velocity. The resulting flow field contains a spherical shock, which is separated from the surface by an isentropic shock layer as shown in Figure 4.1.

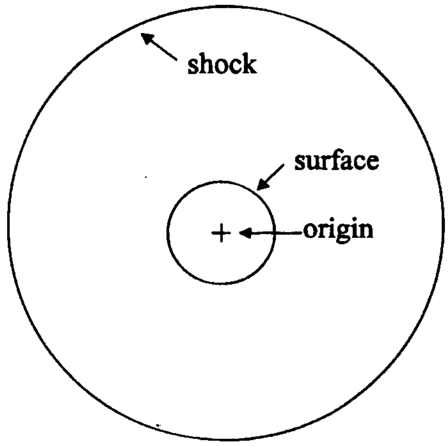


Figure 4.1. Sketch of Problem III.A

The solution to this problem is given by Primakoff (see Courant and Friedrichs, *Supersonic Flows and Shocks*, Interscience Publishers, 1948, p. 424):

$$S = Kt^{2/5}, \quad u = \frac{K}{10t^{3/5}}\left(\frac{r}{S}\right), \quad p = \frac{K^2}{25t^{6/5}}\left(\frac{r}{S}\right)^3, \quad \rho = \frac{4}{3}\left(\frac{r}{S}\right), \quad e = \frac{K^2}{200t^{6/5}}\left(\frac{r}{S}\right)^2$$

where S is the shock radius and $K = S_I/t_I^{2/5}$. The subscript I indicates initial conditions. This problem is cast in 1-D spherical coordinates.

Mesh: The mesh has 500 uniform cells of width $\Delta r = 0.5$

Boundary Conditions: The computational mesh boundaries are located at $r = 0$ and 250. Initial the piston and the shock, respectively, are located at $r_p = 30$ and $S = 30$. The piston location and velocity are prescribed as per the following relations:

$$r_p = S\left(\frac{r_{b_I}}{s_I}\right)\left(\frac{t_I}{t}\right)^{\frac{3}{10}}; \quad S = Kt^{\frac{2}{5}}; \quad u_b = \frac{r_b}{10t}$$

Here K has a value of 1,933.182, and the subscript I denotes initial conditions. The right end boundary conditions do not influence the solution over the duration of the problem.

Initial Conditions: The problem is started at $t = 3.\text{E}{-}5$ with an initial shock radius of $s = 30$ and initial piston location of 30. The following uniform properties are assigned to the flow field: $\rho = 1.$, $e = 1.666667\text{E}{+}3$, $p = 1\text{E}{+}4$, and $u = 0$.

Termination: The calculation is concluded at $t = 3.889\text{E}{-}3$, at which point the piston and shock are located at $r_p = 48.9$ and $s = 210$.

Benchmark: The benchmark is the solution by Primakoff which is exact in the limit of a strong shock. (See Courant and Friedrichs, *Supersonic Flows and Shocks*, Interscience Publishers, 1948, p. 424, for a description of it.)

Output: Compare the computed pressure, density, and velocity at t = 3.889E−3 seconds to Figures 4.2 through 4.4.

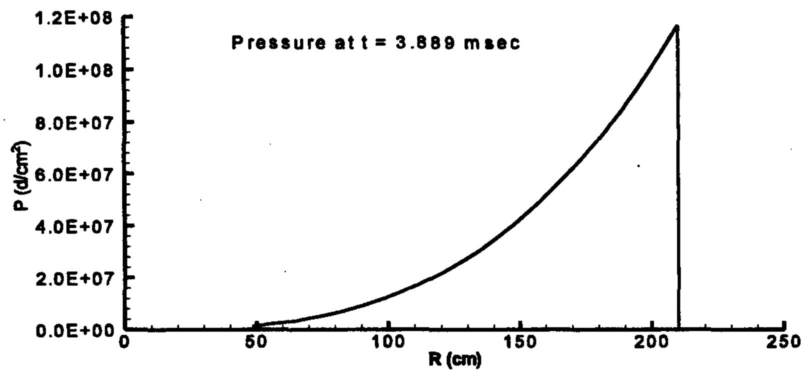


Figure 4.2. Pressure Distribution for Problem III.A

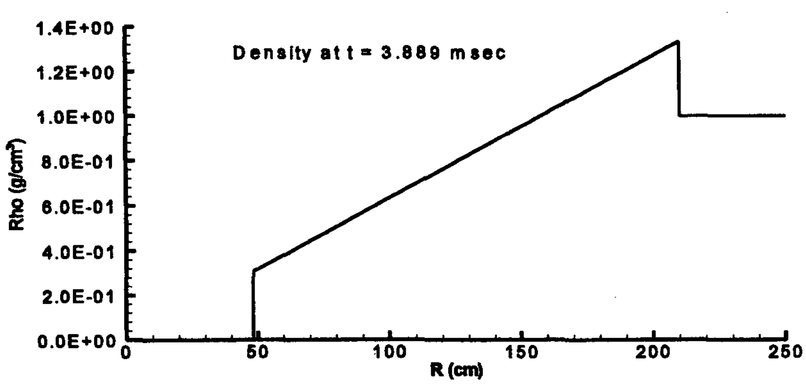


Figure 4.3. Density Distribution for Problem III.A

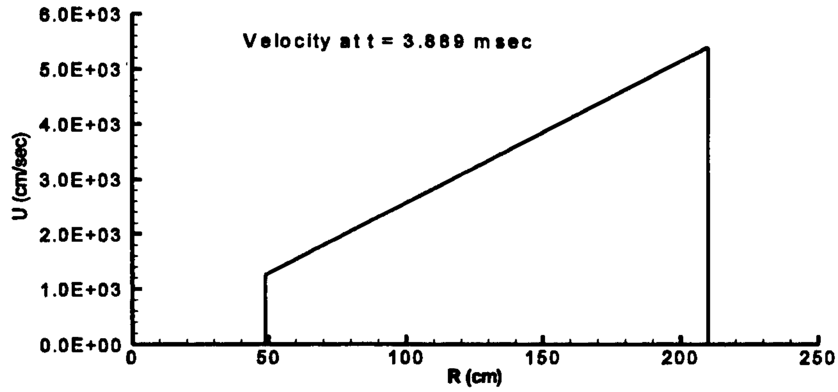


Figure 4.4. Velocity Distribution for Problem III.A

III.B Mixed Material Piston

Description: A planar piston accelerates away from a fluid consisting of a γ law gas, γ = 1.3, and water. The water is sandwiched between two gas regions. Both gas regions are at the same state and the two initial states for the problem are

γ law gas: ρ = 0.035, e = 9.5238E+9, p = 1.E+8, u = 0
Water: ρ = 1.00413030, e = N/A, p = 1.E+8, u = 0

This is cast in planar coordinates with the piston moving along the diagonal of the grid. A schematic of this problem is given in Figure 4.5.

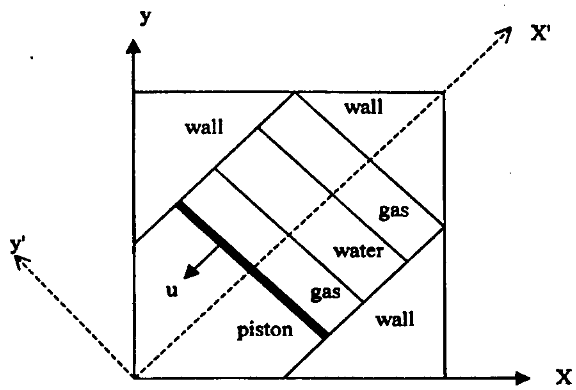


Figure 4.5. Sketch of Problem III.B

Mesh: The mesh is uniform with 200 cells in each direction. The cell dimensions are $\Delta x = \Delta y = 5$.

Initial Conditions: The coordinates for the point shown in Figure 4.6 are given below:

Points	x	y
a	0	292.89322
b	707.1067812	1000
c	1000	707.1067812
d	292.89322	0
e	628.7689399	335.8757211
f	335.8757211	628.7689399
g	477.2970773	770.1902961
h	770.1902961	477.2970773
p1	558.0582617	265.165043
p2	265.165043	558.0582617

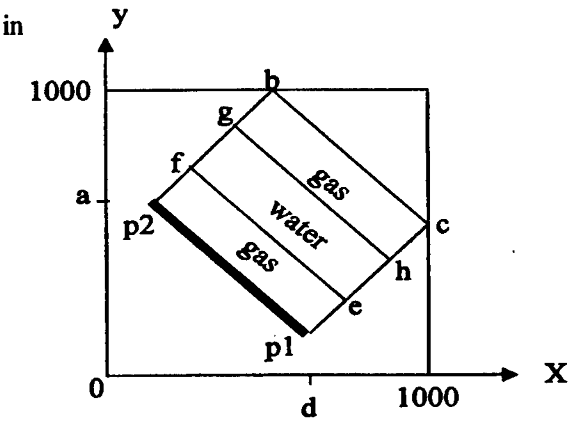


Figure 4.6. Dimensions of Problem III.B

The rectangles g-b-c-h and p1-p2-f-e contain gas while the rectangle f-g-h-e is filled with water.

Boundary Conditions: Reflection conditions are applied to lines a-b, b-c, and c-d. Line p1-p2 represents the piston that is moving at the velocity: $u = v = -3.5355339E{+}4$. Reflection boundary conditions, adjusted for the piston motion, are applied here. Points p1 and p2 move according to the formulas:

$$\text{p1}: x_{p1} = 558.0582617 - (3.535539E{+}4)t;\ y_{p1} = 265.165043 - (3.5355339E{+}4)t$$

$$\text{p2}: x_{p2} = 265.165043 - (3.5355339E{+}4)t;\ y_{p2} = 558.0582617 - (3.535539E{+}4)t$$

Benchmark: The benchmark is the computed 1-D solution of case I.G.

Output: The pressure, density, and velocity along the diagonal are compared to the benchmark solution of Figures 4.7 through 4.9. These comparisons require data at 1.5E−3, 2.5E−3, and 7.0E−3 seconds. In these figures, the distance along the diagonal is measured from the origin (i.e., the lower left corner of the computational mesh).

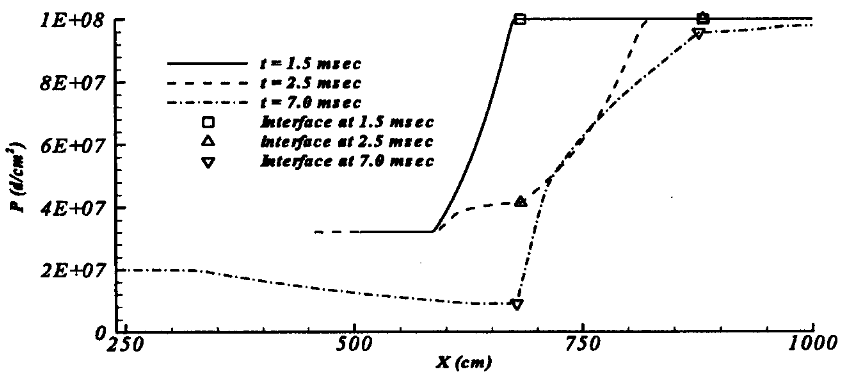


Figure 4.7. Pressure Distribution in Problem III.B

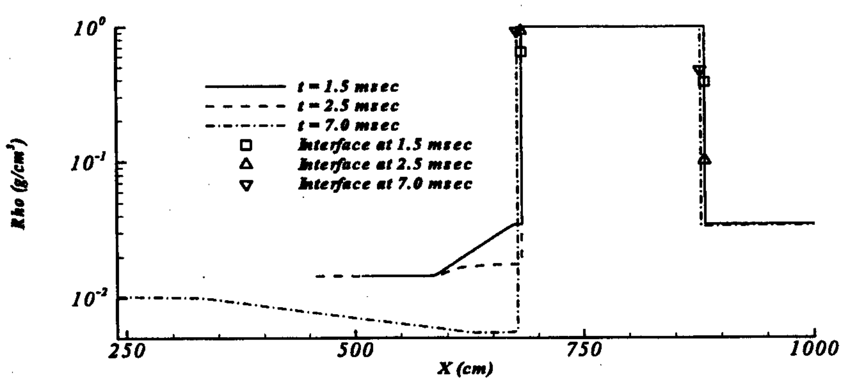


Figure 4.8. Density Distribution in Problem III.B

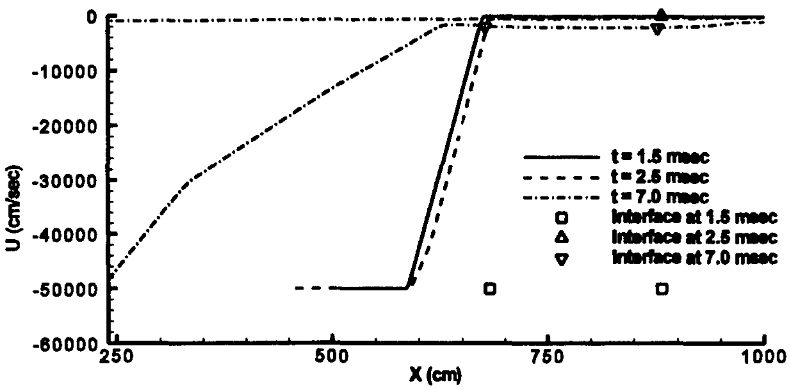


Figure 4.9. Velocity Distribution in Problem III.B

Also provide pressure contour (or color flood) plots spanning the levels pressure levels of 2.E+7 to 1.2 E+8 at 1.5E-3, 2.5E-3, and 7.0E-3 seconds.

III.C Bubble Jetting With a Moving Plate

Description: This problem is the same as the previous bubble jetting problem (Case II.E). However, the plate translates vertically in response to pressure loading on it. The velocity of the plate as a function of time is prescribed using the data in Figure 4.10, which are also tabulated in Appendix A.

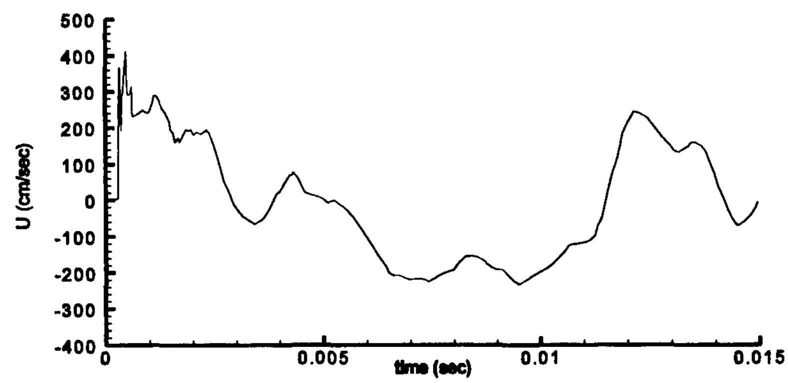


Figure 4.10. Plate Velocity as a Function of Time

Mesh: This computation is done on the non-uniform mesh 2 of Case II.E

r block

Block	*No. of cells*	Δr_{1st}	Δr_{last}	$\Delta r_{i+1}/\Delta r_i$	*Block width*
1	60	0.4333000	0.4333000	1.0000000	25.9980000 center-line
2	40	0.4441325	1.1677330	1.0250968	30.0000000
3	27	1.2144424	3.6515117	1.0432498	60.0000000
4	36	4.0166629	113.9466213	1.1002962	1,210.0000000 outer edge
	sum: 163				1,325.9980000

z block

Block	*No. of cells*	Δz_{1st}	Δz_{last}	$\Delta z_{i+1}/\Delta r_{zi}$	*Block width*
1	35	115.9159143	4.2581130	0.9073948	1,210.0000000 bottom
2	26	3.8710079	1.2223771	0.9549382	60.0000000
3	40	1.1679165	0.4441324	0.9755136	30.0000000
4	90	0.4333000	0.4333000	1.0000000	38.9970000
5	24	0.4441325	0.8470602	1.0284694	15.0000000
6	20	0.8894132	2.3251964	1.0518798	30.0000000
7	40	2.5577160	118.7093678	1.1034030	1,242.0000000 top
	sum: 275				2,625.9970000

The index numbering convention places the point $i = 1$, $k = 1$ on the bottom of the mesh at the centerline.

Boundary Conditions: The outer radial and the top boundaries are not of influence during the duration of the problem. The bottom boundary must be reflective to counter the effect of gravity.

Initial Conditions: All cells contain water in the initial state except for the following blocks of cells, which are filled with JWL gas at the initial state:

I-index	**k-index**	**Volume fraction JWL material**
1-2	164-164	1.0
1-3	160-163	1.0
1-1	159-159	1.0

Benchmark: An unclassified benchmark is not available for this problem.

Output: Show the following:

1. Average bubble radius history. The bubble radius is calculated from

$$r = \left(\frac{3V}{4\pi}\right)^{1/3}$$

where V is the volume of the JWL material.

2. Plate force history (F_p) as a function of time. Here

$$F_p(t) = 2\pi\int_0^R (p_t(r,t) - p_b(r,t))rdr,$$

where p_t, p_b are the pressures on the top and bottom of the plate and R is the plate radius.

3. Plate impulse history (I_p), where

$$I_p(t) = \int_0^t F_p(\tau)d\tau.$$

4. Pressure histories at $r = 0$, 2.54, 5.08, 7.62, 10.16, and 12.70 cm for the complete run ($0 < t < 0.015$).

5. Pressure histories at $r = 0$, 2.54, 5.08, 7.62, 10.16, and 12.70 cm during jetting (e.g., $0.012 < t < 0.015$).

6. Impulse histories at $r = 0$, 2.54, 5.08, 7.62, 10.16, and 12.70 cm for the complete run ($0 < t < 0.015$).

7. Pressure contour (or color flood) plots at 0.0375 t_p, 0.102 t_p, 0.251 t_p, 0.502 t_p, 0.754 t_p, 0.873 t_p, 0.970 t_p, 1.00 t_p, and 1.05 t_p, where t_p is the time to minimum volume. The viewing area should be reflected about the original center of the charge to produce a complete image of the bubble. Each contour plot should be centered on the explosive and should cover a square region 100 cm on a side.

III.D Spherical Piston in 3-D

Description: This problem is the same as case III.A; however, here it is cast in 3-D Cartesian coordinates. To minimize the problem size the solution domain is limited to $x \geq 0, y \geq 0, z \geq 0$. Figure 4.11 shows the problem.

Mesh: The mesh is 3-D with 100 uniform cells in each direction of width $\Delta x = \Delta y = \Delta z = 2.5$.

Initial Conditions: See problem III.A.

Boundary Conditions: See problem III.A.

Benchmark: See problem III.A.

Output: Compare the computed pressure, density and velocity at $t = 3.889\text{E}{-3}$ seconds to Figures 4.2 through 4.4. To demonstrate solution symmetry, plot data along lines ($x = y = 0$), ($x = z = 0$), ($y = z = 0$), ($x = y, z = 0$), ($x = z, y = 0$), ($y = z, x = 0$), and ($x = y = z$).

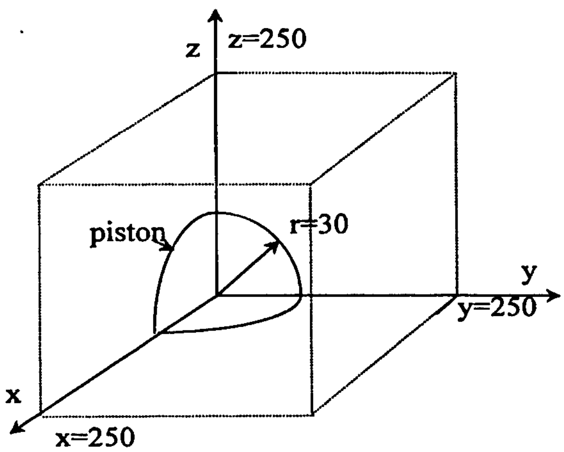


Figure 4.11. Sketch of Problem III.D

5. SUMMARY

Nineteen test cases have been presented that are designed to test the ability of numerical methods to simulate the fluid aspects of underwater explosions and the resulting fluid-structure interaction. The fluid phenomena present in such problems are strong shocks in stiff materials and multiple materials that interact along well-defined interfaces with density jumps as large as 1000:1. The fluid-structure interaction requires that the fluid and structural solution be accomplished in parallel. This is a consequence of the stiffness of water; small deflections in the adjacent structure immediately unload the surrounding fluid.

The test cases are divided into three groups: 1-D with fixed boundaries, 2-D, 3-D with fixed boundaries, and 1-D, 2-D, and 3-D with dynamic boundaries. The 1-D cases consist of single and multi-material Riemann problems, spherical explosions, and moving piston cases. The 2-D and 3-D fixed boundary problems extend many of the 1-D problems to multidimensions as well as adding situations involving bubble jetting, steady state channel flow, and gun blast. The dynamic problems feature moving pistons and bubble jetting adjacent to a translating plate.

The problems described are complete and specify mesh size, assuming a fixed Cartesian mesh. The computational resources required to work most of these problems are relatively small. However, several of the 2-D and 3-D cases will tax most workstations or PCs.

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Appendix A

PLATE VELOCITY FOR PROBLEM III.C

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Time (msec)	Velocity (cm/sec)	Time (msec)	Velocity (cm/sec)	Time (msec)	Velocity (cm/sec)	Time (msec)	Velocity (cm/sec)
0	3.0178227	2.61745	95.06139	7.651007	-206.72079	12.91107	159.94456
0.276846	3.0178227	2.718121	49.794048	7.827181	-197.66731	13.01174	146.36435
0.302013	244.44356	2.818792	25.651486	7.978188	-193.1406	13.03691	140.32873
0.327181	368.17432	2.919463	-9.0534653	8.003356	-188.61387	13.16275	135.80199
0.357685	193.1406	3.020134	-27.160396	8.104027	-172.01583	13.26342	143.34656
0.377517	292.7287	3.145973	-45.267311	8.255033	-155.41782	13.36409	150.89109
0.402685	292.7287	3.422819	-66.392085	8.380873	-153.90891	13.4396	161.45347
0.453356	411.93263	3.598993	-54.320785	8.531879	-156.92674	13.54027	161.45347
0.503356	291.21982	3.674497	-43.758429	8.708054	-167.48909	13.66611	153.90891
0.553691	291.21982	3.775168	-24.142574	8.733221	-173.52474	13.76678	138.81979
0.604027	315.36223	3.926174	16.598021	8.85906	-184.08713	13.84228	113.16831
0.604027	244.44356	4.001678	21.124752	8.959731	-190.12278	13.96812	73.936647
0.629195	232.3723	4.102349	43.758429	9.135906	-193.1406	14.04362	40.740604
0.755034	239.91683	4.228188	67.900997	9.236577	-206.72079	14.19463	9.084E-07
0.855705	248.9703	4.303691	72.427734	9.362416	-221.80991	14.27013	-25.651483
0.90604	244.44356	4.303691	78.463353	9.488255	-232.37227	14.3708	-49.794048
0.981544	241.42574	4.404362	64.883172	9.66443	-220.301	14.44631	-63.37426
1.031879	255.00595	4.479866	46.776254	9.790268	-209.73861	14.49664	-69.409909
1.082215	271.60399	4.580537	21.124752	9.941275	-199.17625	14.64765	-58.847523
1.107383	289.71091	4.706376	15.089109	10.11745	-188.61387	14.79866	-40.740604
1.157718	289.71091	4.88255	9.0534653	10.26846	-175.03366	14.89933	-21.124752
1.233221	274.62178	4.983222	4.5267342	10.41946	-156.92674	14.94966	-4.5267311
1.233221	270.09505	5.10906	-9.0534653	10.57047	-138.81979		
1.283557	256.51486	5.234899	9.084E-07	10.64597	-123.73069		
1.333893	247.46139	5.33557	-7.5445529	10.74664	-120.71287		
1.384228	238.40792	5.486577	-19.61584	10.84731	-119.20396		
1.459731	217.28317	5.637584	-39.231692	11.04866	-114.67722		
1.484899	196.15843	5.763422	-60.356435	11.14933	-108.64157		
1.535235	190.12278	5.914429	-86.007915	11.25	-96.570302		
1.560403	178.05148	6.040268	-110.15048	11.30033	-70.918822		
1.58557	161.45347	6.140939	-128.25743	11.40101	-48.285136		
1.661074	175.03366	6.241611	-149.38218	11.52684	19.615843		
1.686242	161.45347	6.367449	-168.99801	11.65268	79.972266		
1.837248	196.15843	6.442953	-184.08713	11.75336	117.69505		
1.912752	193.1406	6.493289	-199.17625	11.82886	155.41782		
1.963087	196.15843	6.59396	-205.21187	11.87919	187.10495		
2.013423	182.57822	6.744967	-206.72079	12.00503	217.28317		
2.088926	190.12278	6.845637	-212.75644	12.1057	236.899		
2.189597	184.08713	6.971477	-218.79208	12.13087	245.95248		
2.315436	194.64949	7.147651	-215.77426	12.25671	242.93465		
2.365772	188.61387	7.298657	-218.79208	12.43289	230.86335		
2.466443	158.43565	7.399329	-224.8277	12.55872	211.24752		
2.541946	128.25743	7.550335	-214.26535	12.76007	179.56039		

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DEPARTMENT OF THE NAVY
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5216
Ser 420/139
24 Nov 98

From: Commander, Indian Head Division, Naval Surface Warfare Center

Subj: REVISION TO INDIAN HEAD DIVISION TECHNICAL REPORT IHTR 2069

Encl: (1) Distribution Statement Label
(2) Revised Report Pages

AD-B238 684

1. Indian Head Division technical report IHTR 2069 has been approved for PUBLIC RELEASE. This letter will serve as notification to you of this change. Please make the following updates to your copy of this report:

a. Affix the label given in enclosure (1) to the front cover (to show the new distribution statement),
b. Replace the Report Documentation Page (enclosure (2)), and
c. Replace Page 1/2 (enclosure (2).

2. If you have any questions regarding this revision, please contact Dr. Andrew Wardlaw, Code 420, at (301) 744-4756.

J.B. Almquist
J. B. ALMQUIST
By direction

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